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Computer-aided methods for determining drilling sequences of non-turret, multiple spindle, numerical control drilling machines

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COMPUTER-AIDED METHODS FOR DETERMINING DRILLING SEQUENCES OF NON-TURRET, MULTIPLE SPINDLE, NUMERICAL CONTROL DRILLING MACHINES

by

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CERTIFICATE OF APPROVAL

This thesis is accepted and approved in partial fulfillment of the requirements for the degree of Master of Science.

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ABSTRACT

The use of multiple spindle, numerically controlled, drilling machines, notably in printed wiring board manufacturing, has resulted in the need for efficient methods for finding drilling sequences when several hole sizes are to be drilled in one machine setup. Of the two varieties of multiple spindle machines existing, turret and non-turret, the non-turret machines are given the primary emphasis.

The difficulty in finding drilling sequences that minimize the total machine cycle time, for a multiplicity of spindles and hole sizes, is complicated even more when several spindles are capable of drilling the same hole size and one of these spindles must be assigned to drill each hole. This pseudo-traveling salesman problem is solved for two types of non-turret machines using a two part heuristic algorithm developed in this paper. The flexibility of the algorithm, which allows a part programmer the option of using just the first part to obtain a solution for small production applications and/or problems involving up to 2000 holes, or the use of both parts to further minimize the machine cycle time for large production applications involving up to 200 holes, makes it a practical addition to computer-aided part programming systems used for automatically generating numerical control coded tapes. Since the second part of the algorithm is essentially an existing traveling salesman problem algorithm that takes a considerable amount of computer processing time to obtain a solution, the results of simulated problems are compared for both parts of the algorithm in order to provide the user

a basis for determining whether to use the first part or both parts for a particular application.

CHAPTER I.

INTRODUCTION

Multiple spindle, numerically controlled, drilling machines have been used for several years to drill the component holes in printed wiring boards. One of their prime advantages is the capability of drilling several hole sizes without machine shutdown to change drill bit sizes, however, one drawback to their use is the difficulty encountered in determining efficient drilling sequences that result in acceptable machine cycle times for drilling a printed wiring board. Recent success in applying the traveling salesman problem solution to single spindle machines, which has resulted in significant manufacturing cost savings due to improved drilling cycle times, has made it desirable to search for similar techniques for use on multiple spindle machines. The purpose of this paper is to explore the difficulties of finding good drilling sequences for these machines, and to develop and evaluate a proposed method of automatically generating them for two types of non-turret multiple spindle machines currently in use by industry today. It is felt that the reduction of setup costs offered by these machines, coupled with good drilling sequences, makes the endeavor worthwhile.

It is assumed the reader is familiar with the basic concepts of numerical control (N/C) machinery and what is meant by point-to-point positioning systems, traveling table, spindle, part programming, and N/C coded tape.

CHAPTER II.

BACKGROUND AND STATEMENT OF PROBLEM

A. History of Computer-Aided Part Programming

From the time the first numerical control machine prototype was demonstrated by M.I.T. in 1952, it was recognized that efficient means of generating the numerical and machine command data would be required, particularly if the parts to be made were very complex. In the last decade a great deal of effort has been concentrated on the preparation of the coded tape required to produce a finished part. It was recognized that the quality of the coded tape and the time spent producing it could make the difference between profit and loss. The reasons were evident-excessive tape preparation time would result in lost revenues from idle machines waiting for tapes and hastily or poorly prepared tapes could produce defective or substandard parts resulting in lost productivity and excessive scrap. The search for efficient tape preparation methods has resulted in a large variety of computer-aided part programming systems. Their impact has been to greatly reduce the time and number of errors in tape preparation by relieving the part programmer of the tedious and inherently error ridden task of generating the detailed numerical and machine command data required by the machines. The trend has been, and will continue to be, toward building computer-aided systems that are programmed to do the routine functions a part programmer normally does, and in some cases, functions a part programmer is unable to do because of the complexity of the part. The ultimate goal is for fully automatic part programming systems that will accept part information at the design stage and convert it into a complete control tape or set of instructions that has been optimized in terms of feeds, speeds, machine movements, etc. It is not the purpose of this thesis to evaluate the pros and cons of computer-aided part programming systems or to justify their use. This has been done elsewhere (8). It is only necessary to realize that the results of the thesis are intended to be used in such systems. The interested reader is referred to a recent survey conducted by the Institute of Science and Technology at the University of Michigan (8). The survey reviews the task of part programming, its importance, and the computer-aided part programming systems that are available. A part programming system not covered by the survey but of importance to the thesis is a specialized system called CAPP (Computer-Aided Part Programming) recently introduced by the Western Electric Company (3). Its sole purpose is to speed the preparation of coded tape for point-to-point, N/C drilling machines used to drill component holes in printed wiring boards (PWB). One of the interesting features of this system is its compatibility with a Bell Telephone Laboratories automated graphics computer program whose function is to provide input for N/C drafting machines capable of producing drawings and artmasters. Together the systems operate in the following manner: once the design for a new PWB is completed, the geometric information (circuit paths, hole locations, etc.) is encoded for input to the graphics program. The resulting output from this program consists of the necessary data for the drafting machines and a tabulated listing, in computer-usable form, of the hole locations and sizes sorted by ascending X,Y coordinates. This tabulated data is then entered as input, along with part programming data, to CAPP which produces the necessary coded data for drilling the PWB with N/C machinery. One of the problems with this arrangement was that drilling holes by using the sequence in which the data was entered (i.e., in ascending X, Y coordinates) would result in excessive machine table travel. To overcome this, optimizing routines were provided to calculate the best sequence to use in order to minimize machine travel distance, or equivalently, machine cycle time. One of these routines is based on a heuristic traveling salesman problem algorithm developed by Shen Lin of Bell Telephone Laboratories (7).

CAPP is also usable as a stand alone system whereby the part programmer enters the hole-drilling data in the form of individual hole coordinates and/or patterns. In this mode CAPP manipulates the patterns and develops the individual X, Y coordinates of the holes. The system then uses the optimizing routines as before, or the sequence specified by the programmer. Since the optimizing routines are lengthy in terms of computation time, the economic tradeoffs of computer processing costs vs. production cost savings requires evaluation before a decision is made to use the routines. In any event, their use can result in significant savings in manual part programming time, production costs due to a reduced machine cycle time, and maintenance costs due to the reduction of wear realized by moving the table less.

B. Multiple Spindle Machine Descriptions

There are essentially two types of point-to-point multiple spindle, N/C drilling machines--the turret and non-turret type. The turret machine derives its name from the fact that the spindles are arranged around the circumference of a large wheel or turntable which is perpendicular to the workpiece. Since only one spindle at a time can be actuated (there is only one position where the spindle is perpendicular to the PWB), the desired spindle is indexed by rotating the wheel until it is in the working position at which time the spindle motor is engaged and drilling commenses. In contrast, the non-turret machines have their spindles mounted in a plane (which is parallel to the workpiece) such that all the spindles are perpendicular to the workpiece simultaneously. Depending on the type of machine and controller, any or all spindles can be actuated simultaneously to drill one or more holes in the workpiece. For both types it is possible for each spindle to contain a different drill bit size or any other combination of drill bit assignments.

Since it will be required to find a drilling sequence which results in minimum machine cycle time, it is necessary to understand the steps these machines go through in order to drill a hole. Assuming hole i has been drilled with spindle k and the machine is now directed to drill hole j with spindle m, the drilling procedures for both types are as follows:

Turret Type: One possible sequence of events consists of moving the table such that hole j is positioned directly under the working spindle. If the spindle used to drill hole i is the same as that required by hole j (i.e., $m = k$) then the spindle is actuated and the hole is drilled. If spindle $m \neq$ spindle k then the turret wheel is rotated until spindle m is in position to drill hole j, the spindle is actuated, and the hole is drilled. This procedure is a mutually exclusive, two step operation. Another possible sequence of events allows the indexing of spindle m (assuming $m \neq k$) while the table is being moved to position hole j under the working spindle.

Non-Turret Type: The drilling procedure for this type consists only of positioning hole j under spindle m, actuating the spindle and drilling the hole. If other holes are simultaneously located under spindles with the proper size drill bits, they can either all be drilled simultaneously, or in sequence without table movement (because of sequential requirements of some machine-controller combinations, a small incremental table movement may be required before a second hole can be drilled).

Understanding the movements of these machines permits computation of the machine time required to drill any hole given a hole has been drilled. With this knowledge it is then possible to utilize existing mathematical formulations to minimize the total machine cycle time subject to the requirement that all holes must be drilled and that the ending point of the cycle must be the starting point (thus allowing the recycling of the control tape).

Excluding reference to multiple spindles for the moment, the preceding paragraph is essentially a description of the well known "Traveling Salesman Problem" (TSP). The problem got its name from the following situation: A traveling salesman must leave his home office and visit n-1 cities, once and only once, and then return. Being a good salesman he realizes that the less time spent traveling from city to city the better. His problem of course is to choose the route, or tour of the cities, that results in the minimum time or distance traveled.

Mathematically, the problem may be stated as: Given a cost matrix $C = \left\{ c_{ij} \right\}$, where c_{ij} is the cost of going from city i to city j ($i, j = 1, 2, \ldots, n$), find a permutation $s = \left\{ i_1, i_2, \ldots, i_n, i_1 \right\}$ of the integers 1 through n that minimizes the quantity

$$\sum_{(i,j) \in s'} c_{ij} = c_{i_1, i_2} + c_{i_2 i_3} + \ldots + c_{i_n i_1}$$

where $s' = \left\{ (i_1, i_2), (i_2, i_3), \ldots, (i_n, i_1) \right\}$ is the pairwise representation of s.

The analogy, at least for single spindle drilling machines, is obvious. All that is really required is a method of calculating the cost matrix C, and an efficient algorithm for finding the optimal permutation or drilling sequence. As already pointed out, Lin's algorithm is being used successfully in CAPP for this purpose.

For multiple spindle machines the analogy is not quite as obvious. Also, there are at least four conditions to consider when optimizing cycle time for these machines (two of which do not apply to the turret machine).

1. Drilling is to be done with a different size drill bit in each of the spindles to be used.

2. Drilling is to be done with the same size drill in more than one spindle.

3. Same as condition 1 except any or all spindles can be used to drill holes simultaneously (non-turret machines only).

4. Same as condition 2 except simultaneous drilling can occur (non-turret machines only).

Conditions 3 and 4 are felt to be important only in specialized situations where the layout of holes on the PWB have been designed to take advantage of simultaneous drilling. When it can be done, a cluster of holes can be considered as one hole, and the effective size of the sequencing problem is reduced. While these situations are interesting, it is felt that the majority of PWB drilling involves randomized hole layouts, at least for the types of machines being considered. Under these circumstances, it appears unlikely that very many holes will be spaced such that simultaneous drilling can occur, and consequently it remains questionable whether or not such occurrences should be considered. Accordingly, the remainder of the thesis shall be concerned only with the first two conditions.

For condition one, it can be shown that a cost matrix C can be computed and a TSP solution procedure used to find the optimal sequence. Condition two on the other hand, is a pseudo-traveling salesman problem and consequently cannot be transformed into a TSP formulation directly. It is this second condition that is explicitly considered in the thesis and for which a heuristic solution procedure is proposed and evaluated when applied to two types of non-turret drilling machines. While empirical data was not gathered for the turret type machines it is felt that the solution procedure is applicable to this type of machine with only minor modifications.

C. Metrics

Before proceding to the statement of the problem, it is first necessary to establish a method of measuring machine cycle time given a drilling sequence is specified.

It will be assumed that the time it takes to actually drill n holes is constant regardless of what sequence is chosen and further that this time is not subject to reduction by optimization techniques. This assumption implies that when a spindle is actuated, it attains its required rotational speed instantaneously. Since table travel velocities are relatively slow (in the order of 200 inches/minute) it is felt that the assumption is a valid one.

Disregarding then the time required to lower the spindle (or raise the table or both), drill the hole, and retract the spindle, the remaining time is involved with positioning the PWB under the desired spindle (for turret machines the time to index a spindle will also be a consideration).

One further assumption that has been made is that table travel velocity is considered constant over all distances traveled. This assumption is valid over most of the travel distances involved, however, nonlinearities usually do exist for small movements of the table (typically less than one inch). For the machine-controller combinations being considered, these nonlinearities are not severe enough to invalidate the assumption. There are configurations where this assumption is decidedly not valid, in which case the table velocities versus distance traveled must be explicitly considered when calculating the positioning time between holes.

With these assumptions in mind, what is needed is a metric for measuring positioning time. It is helpful to examine single spindle machine metrics first. If it is assumed that hole i has been drilled and hole j is to be drilled next, then the time required for the table to move from hole i to hole j is given by:

$$t_{ij} = \max\left(\left| X_i - X_j \right| , \left| Y_i - Y_j \right| \right)/R$$

where R = table travel velocity in inches/minute (ipm) for each axis.

X_i, Y_i = absolute X,Y coordinates, relative to machine origin, of hole i, i = 1, 2, ..., n.

Letting $\left|X_i - X_j\right| = \Delta X$, the reason $t_{ij} \neq \sqrt{\frac{(\Delta X^2 + \Delta Y^2)}{R^2}}$ is because of the machine design. In point-to-point N/C machines (assuming $\Delta X, \Delta Y \neq 0$), two modes of travel are possible. In less sophisticated systems the table must first move along the X axis and then along the Y axis in which case $t_{ij} = (\Delta X + \Delta Y)/R$. For the more sophisticated systems, which are being assumed, the table travels first along the hypotenuse of a 45 degree triangle whose sides are given by min $(\Delta X, \Delta Y)$ and then finishes the positioning along the X or Y axis. Under this system the actual distance traveled is given by

$$\min(\Delta X, \Delta Y)\sqrt{(2)} + \begin{cases} \Delta Y - \Delta X & \text{if } \Delta X < \Delta Y \\ \Delta X - \Delta Y & \text{if } \Delta Y < \Delta X \end{cases}$$

However, since this type of system applies the same rate of travel along the X and Y axis simultaneously when moving along a 45 degree angle, the actual time is given by

$$t_{ij} = \min\left\{(\Delta X, \Delta Y)\sqrt{(2)}/R\ \sqrt{(2)}\right\} + \begin{cases} (\Delta Y - \Delta X)/R & \text{if } \Delta X < \Delta Y \\ (\Delta X - \Delta Y)/R & \text{if } \Delta Y < \Delta X \end{cases}$$

$$= \begin{cases} (\Delta X + \Delta Y - \Delta X)/R & \text{if } \Delta X < \Delta Y \\ (\Delta Y + \Delta X - \Delta Y)/R & \text{if } \Delta Y < \Delta X \end{cases}$$

$$= \max(\Delta X, \Delta Y)/R$$

Since the ultimate objective is to minimize total machine cycle time, and since a constant travel rate, R, has been assumed, it is equivalent to use a cost measure of effective distance traveled, in which case, the "cost" of going from hole i to hole j is given by

$$d_{ij} = \max(|X_i - X_j|, |Y_i - Y_j|)$$

and the total cycle time for drilling n holes (excluding actual drilling time) is given by

$$\sum_{(i,j)\in s'} d_{ij}/R$$

where $s' = \left\{(i_1, i_2)\ ,\ (i_2, i_3)\ ,\ \ldots\ ,\ (i_n, i_1)\right\}$.

With multiple spindle machines the metrics are more complex since it is necessary to include the spindle requirements when moving from hole i to hole j. Assuming as before that hole i has been drilled with spindle k and hole j must be drilled with spindle m, the time required to accomplish this for turret machines is given by

$$t(i|k,\ j|m) = \max\left\{ (|X_i - X_j|)/R + t_{k,m}\ ,\ (|Y_i - Y_j|)/R + t_{k,m} \right\}$$

where $t(i|k,\ j|m)$ = time required to move from hole i given hole i was drilled with spindle k to hole j given spindle m is to be used to drill hole j.

$t_{k,m}$ = time required to index spindle m into the working position given spindle k is in the working position.

This metric is for the type of machine that must perform its movements sequencially (i.e., first move the table then the turret or vice versa).

For the machine that can rotate the turret during table movement, the time is given by

$$t(i|k,\ j|m) = \max\left\{\max\ (|X_i - X_j|;\ |Y_i - Y_j|)/R,\ t_{k,m}\right\}$$

While it would be possible to reduce both metrics to effective distance traveled as in the single spindle machine, no computational efficiency could be gained by doing so.* Since there appears to be considerable variation between methods of operation for different turret machines, the practitioner should fully investigate each machine-controller configuration before choosing a metric.

Two types of non-turret machines are being considered in the thesis. One type has its spindles arranged in-line (e.g. all along the X axis), and the second type has its spindles arranged on a rectangle (e.g. one spindle located on each corner). These two types have been dubbed the In-Line and Quad machines respectively.

An example of an In-Line machine is the Edlund Model NPB, N/C drilling machine manufactured by the Monarch Machine Tool Company, Edlund Division (address: Cortland, New York 13045). Models NPB and NPB-100 are sixteen spindle machines consisting of four work stations with a cluster of four spindles/work station (all the spindles arranged in a straight line). This arrangement permits simultaneous drilling of four identical PWB, one per work station, with stacking of four PWB/work station permitted. From the standpoint of optimizing cycle time, only one work station with up to four spindles need be considered.

An example of a Quad machine is the Gardner-Denver, 15J-2000 Series Grid Drill manufactured by the Gardner-Denver Company (address

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*Dimensional analysis reveals why--consider the distance between m and k to be expressed in radians and turret velocity in radians/minute, then normalize the metrics.

for information: Wire Wrap Division, 1333 Fulton Street, Grand Haven, Michigan 49417). This machine is also capable of up to sixteen spindles with the standard arrangement consisting of four work stations with a cluster of four spindles/work station. With this configuration, the four spindles in each work station are arranged in a square array. Figure 1 represents a top view of the two types of machines.

From Figure 1, and considering only one work station, it can be seen that the spindles are spaced a fixed distance from one another and further that each spindle's X, Y coordinates can be defined relative to origin of the X, Y axis. Defining spindle #1 as having X, Y coordinates (0,0), the coordinates of the other spindles are shown in Figure 2.

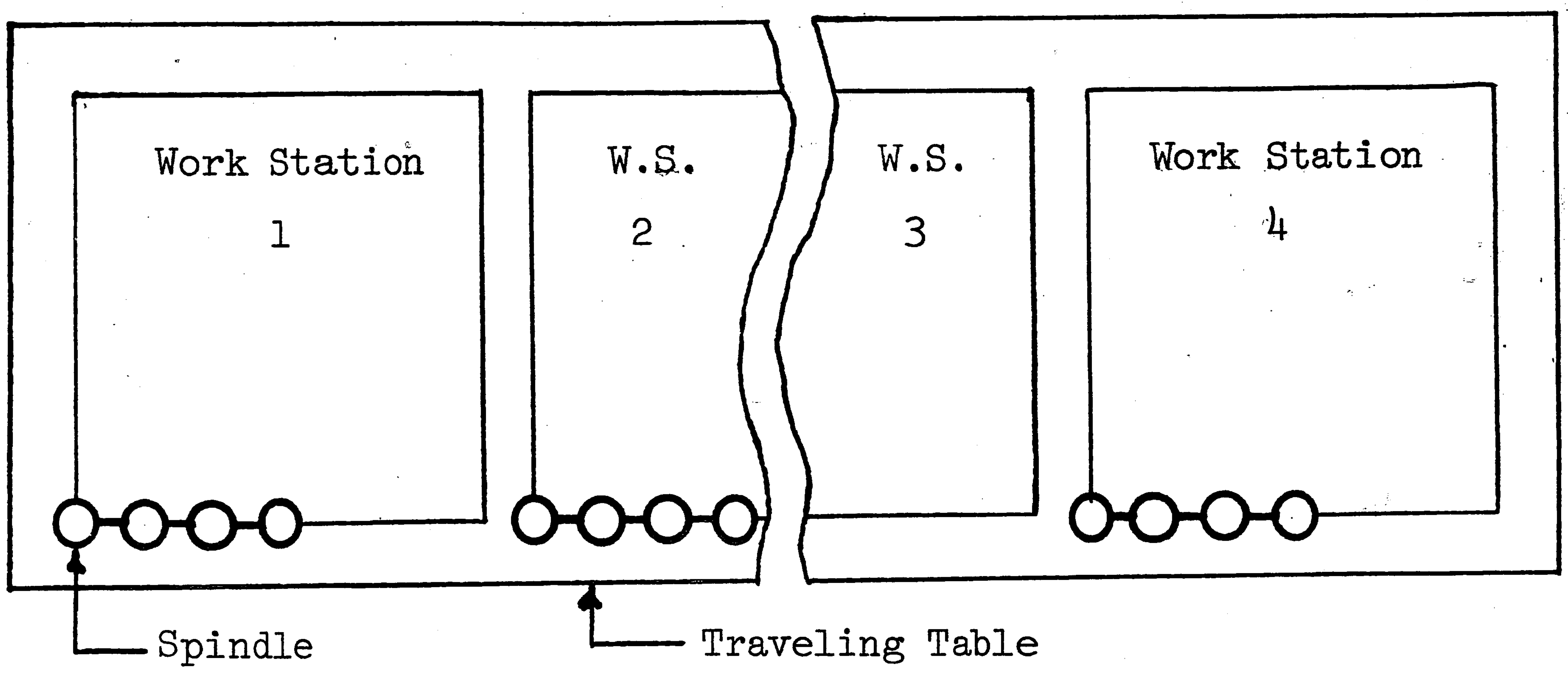
It now becomes obvious that when the absolute X, Y coordinates are known for one spindle, the absolute coordinates of the other spindles can be easily calculated. Accordingly, the time to move from hole i to hole j is given by

$$t(i|k, j|m) = \max(|X_i + (SX_m - SX_k) - X_j|, |Y_i + (SY_m - SY_k) - Y_j|)/R.$$

or equivalently

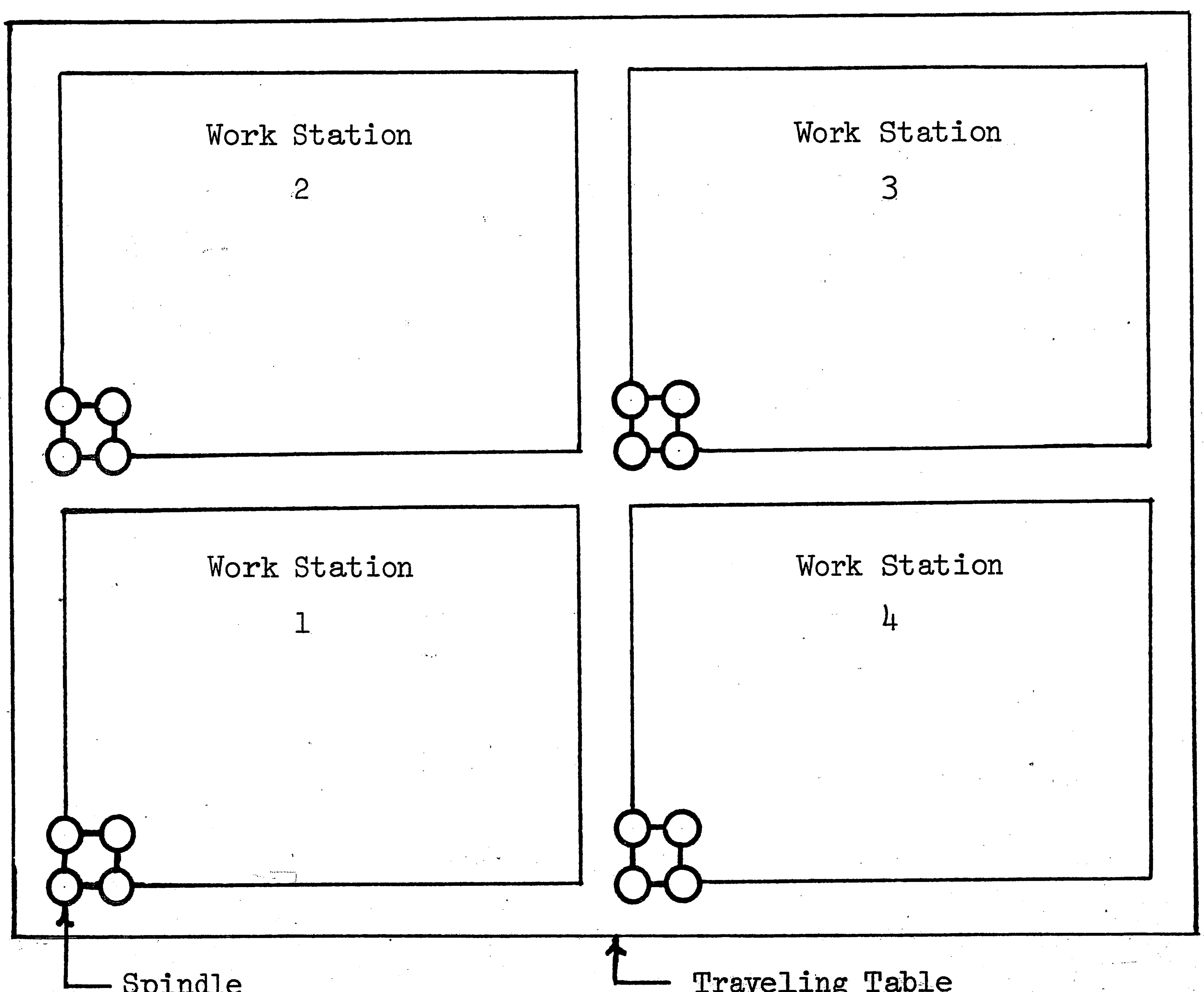
$$d(i|k, j|m) = \max(|X_i + (SX_m - SX_k) - X_j|, |Y_i + (SY_m - SY_k) - Y_j|).$$

where $d(i|k, j|m)$ = effective distance from hole i, given spindle k was used to drill hole i, to hole j, given spindle m is to be used to drill hole j.



(a)

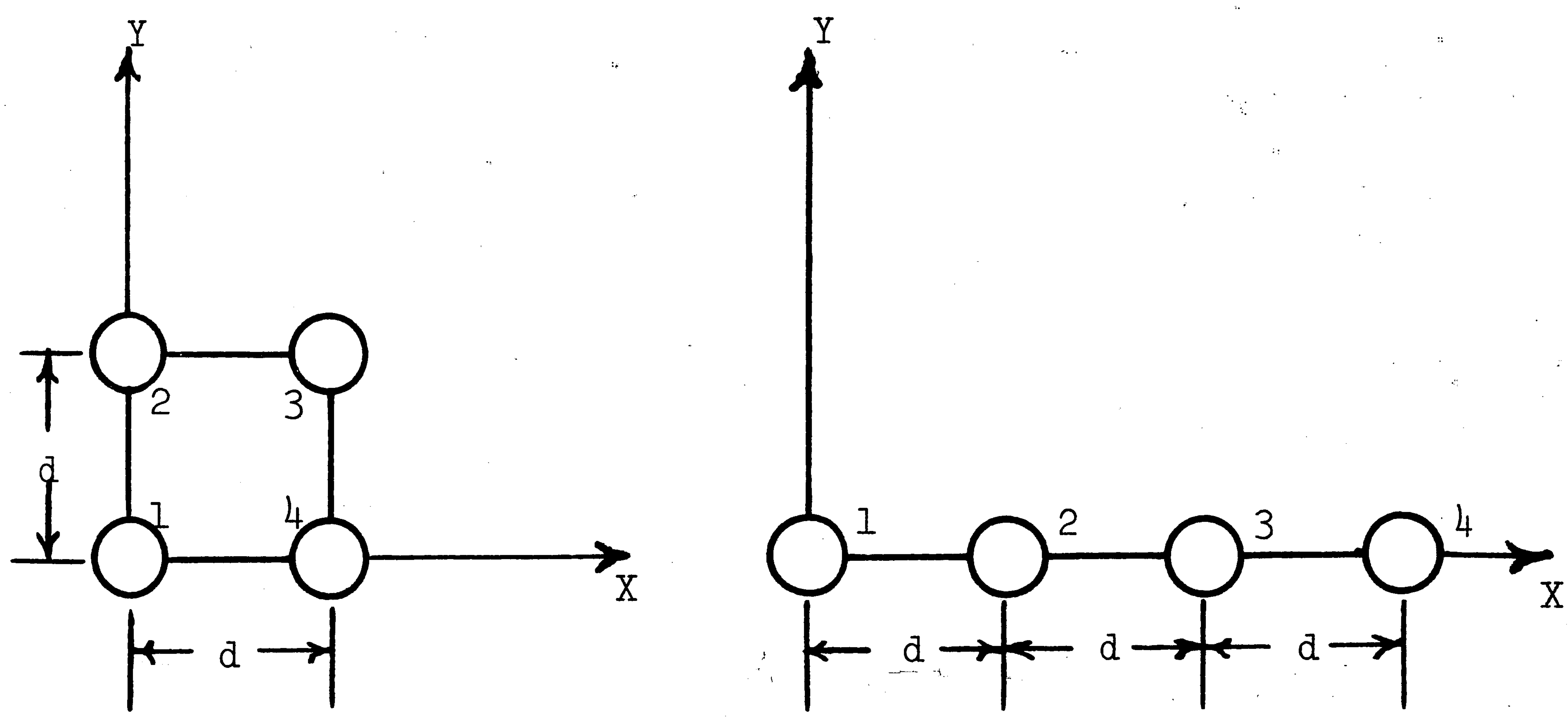
IN-LINE MACHINE



(b)

QUAD MACHINE

FIG. 1. TOP VIEW OF TWO TYPES OF NON-TURRET MACHINES.



Spindle	(SX,SY)
1	(0,0)
2	(0,d)
3	(d,d)
4	(d,0)

(a)

Quad Machine

Spindle	(SX,SY)
1	(0,0)
2	(d,0)
3	(2d,0)
4	(3d,0)

(b)

In-Line Machine

FIG. 2. ONE WORKSTATION FOR TWO TYPES OF NON-TURRET DRILLING MACHINES SHOWING COORDINATE DEFINITIONS OF EACH SPINDLE.

SX_m, SY_m = absolute X, Y coordinates of spindle m relative to the origin given the spindle cluster is at the origin, $m = 1, 2, 3, 4$.

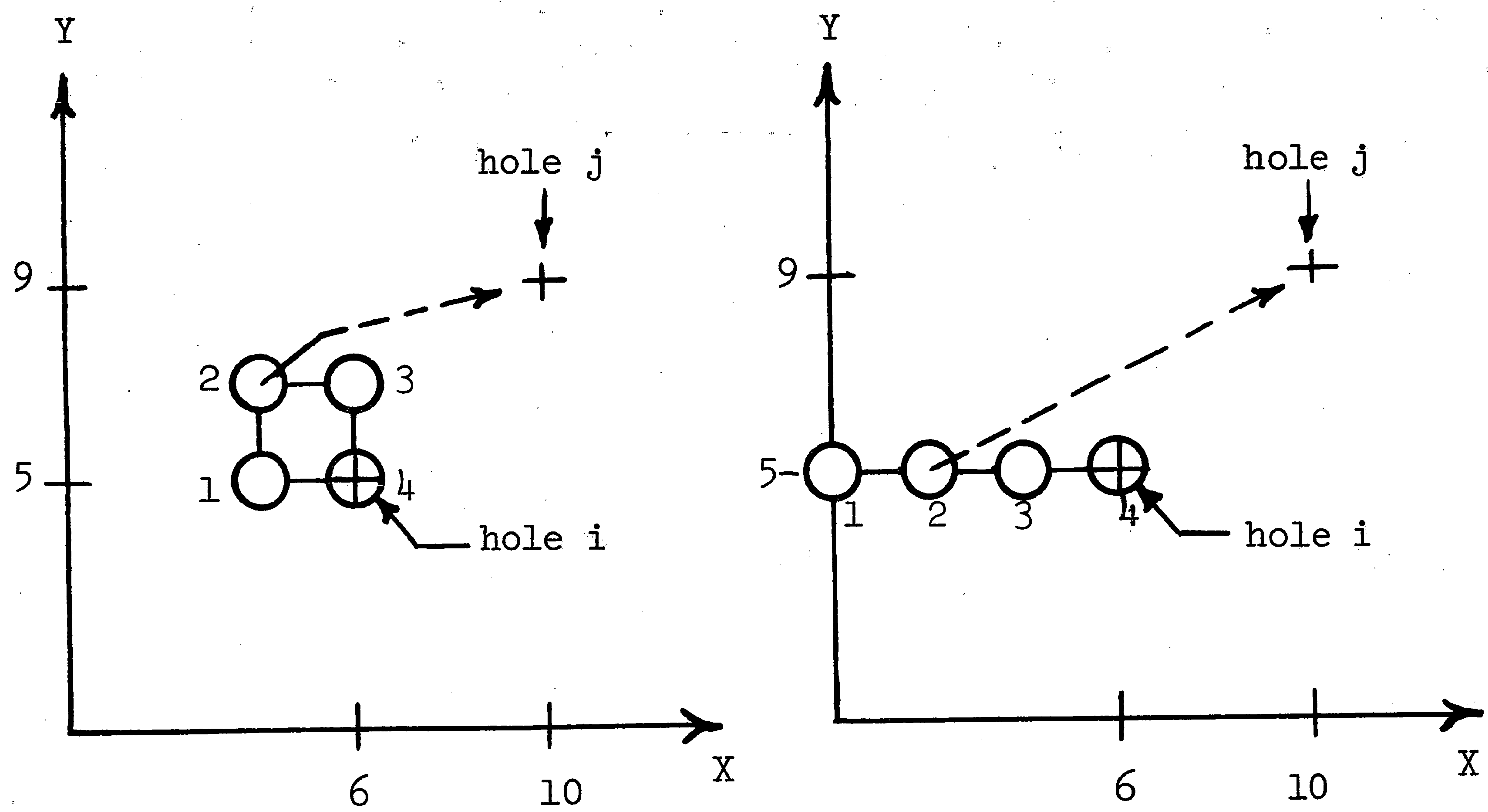
and the quantities $(X_i + SX_m - SX_k)$, $(Y_i + SY_m - SY_k)$ are simply the absolute coordinates of spindle m given k is at coordinates (X_i, Y_i). An example of the use of this metric is given in Figure 3 (assume the spacing between spindles, d, is two inches for both machines). As can be seen from Figure 3, the metric applies equally well to both types of machines even though specification of Y coordinates for the In-Line machine spindles is unnecessary. The metric is actually applicable to any number of spindles or any possible arrangement of the spindles providing no negative coordinates are given for a spindle when the spindle cluster is at the origin. This does not imply the center of the cluster is at the origin, but instead that at least one spindle lies on the X axis (or Y axis or both) and is as close to the origin as possible without other spindles leaving the first quadrant.*

Using this metric, the total machine cycle time, excluding actual drilling time, is given by

$$\sum_{(i|k,j|m) \in s'} d(i|k,j|m)/R$$

---

*Consider for example a two inch radius circular array of four spindles whose coordinates are defined as $SX_1, SY_1 = (2, 0)$, $SX_2, SY_2 = (0, 2)$, $SX_3, SY_3 = (2, 4)$, and SX_4, $SY_4 = (4, 2)$.



$$d(i|4,\ j|2) = \max\begin{cases} |6+(0-2)-10| \\ |5+(2-0)-9| \end{cases}$$

$= 6$ inches

$$d(i|4,\ j|2) = \max\begin{cases} |6+(2-6)-10| \\ |5+(0-0)-9| \end{cases}$$

$= 8$ inches

(a) QUAD MACHINE

(b) IN-LINE MACHINE

FIG. 3. ILLUSTRATION OF EFFECTIVE DISTANCE CALCULATION BETWEEN TWO HOLES REQUIRING DIFFERENT SPINDLES. SPACING BETWEEN SPINDLES FOR EACH MACHINE IS 2 INCHES.

where $s' = \left\{ (i_1|k_1 , i_2|k_2) , (i_2|k_2 , i_3|k_3), \ldots , (i_n|k_n, i_1|k_1) \right\}$

and the k's represent the spindle number used to drill the corresponding hole.

D. Statement of the Problem

The statement of the problem and the solution procedure to be presented are constrained by the following assumptions:

1. The individual X, Y coordinates of each hole and their corresponding hole sizes are available as input or as generated by pattern manipulating processors available in systems similar to CAPP.

2. The number of spindles to be used and their X, Y coordinates relative to the origin is provided as input information (for turret machines it is assumed the indexing times are given).

3. The drill bit sizes are assigned to the available spindles by the part programmer prior to entry into the solution procedure. If more than one spindle is assigned the same size drill bit, no arbitrary assignment of these spindles will be made to the holes affected.

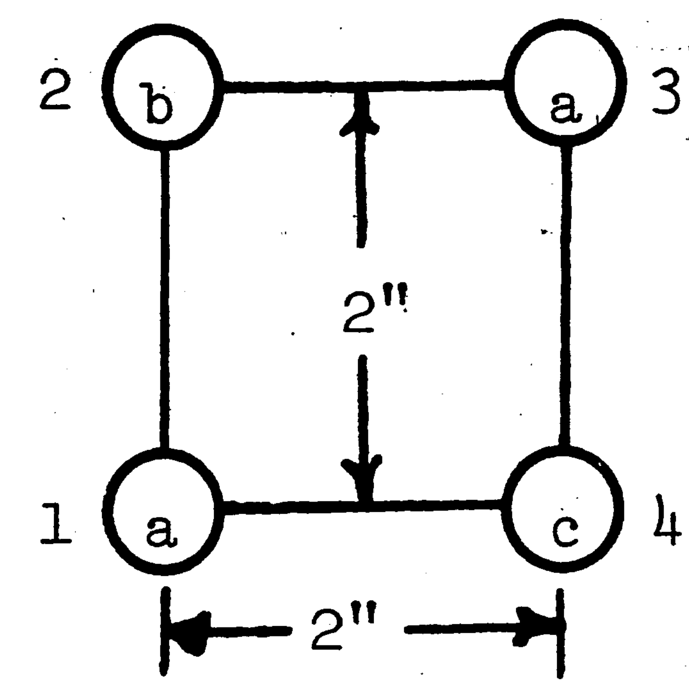
Assumption 3 is made to clarify the type of problem being considered. The alternative to this assumption is to allow the solution procedure to determine which drill bit size to assign to each spindle in order to yield the lowest cycle time possible. While this would be a valuable addition, it was felt the amount of computation time required for one assignment of drill bits to spindles would be too lengthy to allow reiteration of the procedure for other possible combinations of drill bit assignments. Therefore, the assumption has been made.

The specific problem considered in this paper is essentially condition two of the previous section. The problem is: given that more than one spindle is assigned the same size drill bit and several hole sizes are to be drilled, determine which of the spindles containing the same drill bit size should be assigned to drill each hole and find a drilling sequence that together results in the minimum total effective travel distance (or time). Further development of both this problem, and the problem presented by condition one, is given below.

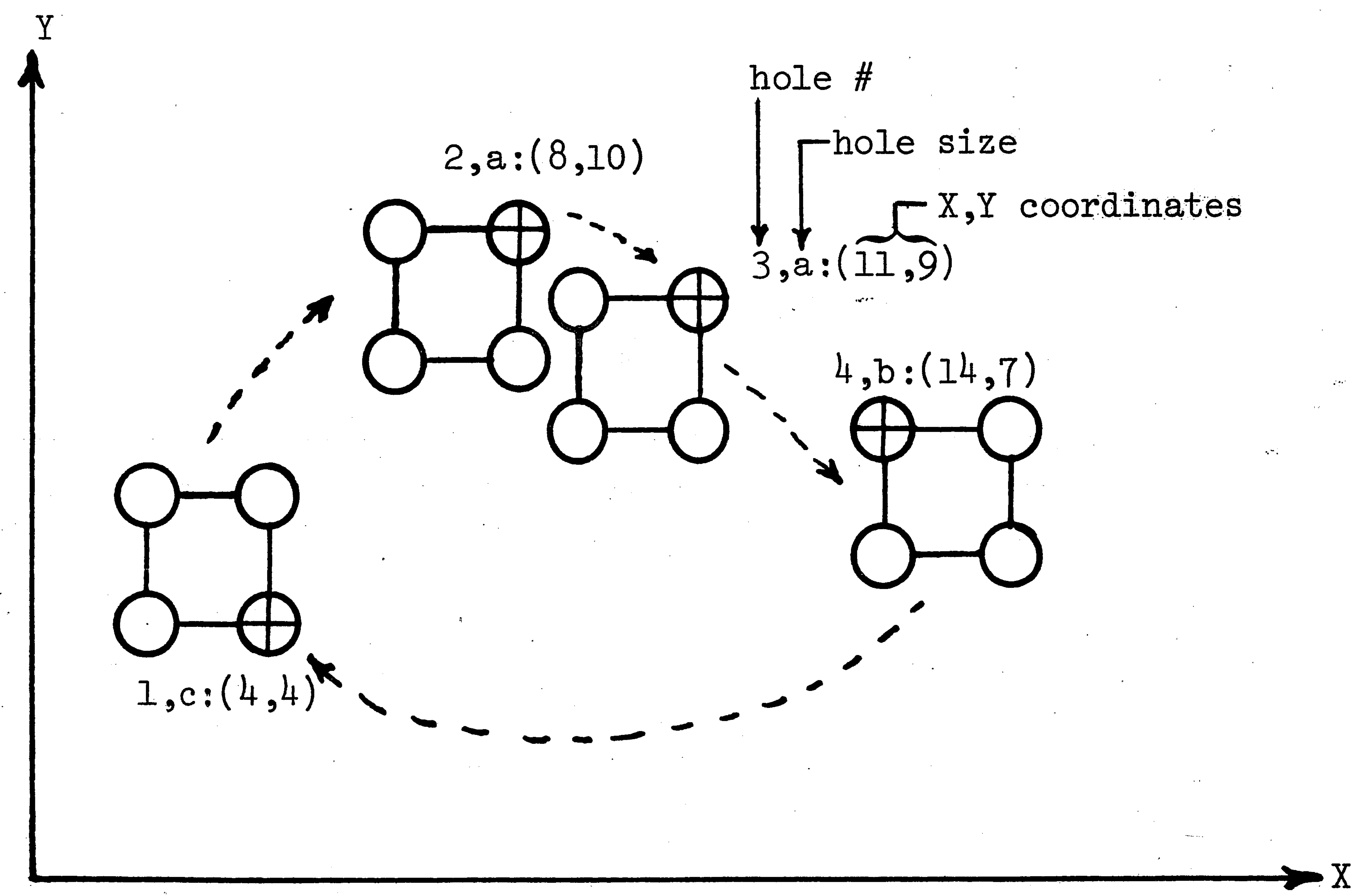
Assume that an efficient TSP is available for finding an optimum sequence. The use of this algorithm requires a "cost" matrix that specifies the cost of going from hole i to hole j (t_{ij} or d_{ij}) for all i and j, i $\neq$ j (a standard TSP assumption). Use of the metrics previously defined can provide this, but the requirement also implies that there is one and only one cost associated with going from hole i to hole j which is equivalent to saying there is only one road between city i and city j. Condition one of section B satisfies this requirement. To see why, assume three different hole sizes are to be drilled and that three spindles are to be used (i.e., each spindle will contain a different size drill bit). Under these conditions, one and only one spindle is available for drilling each hole, and since the hole size for each hole is known (assumption 2) it is known which spindle will drill each hole. Consequently the time required to go from hole i to hole j, using the spindles dictated by the hole sizes, can be readily calculated (for all i and j) and it will in fact be the only time possible. The conclusion to be drawn is that condition one can be formulated directly into a TSP and hence can be solved directly by existing algorithms once the cost matrix is calculated.

Condition two is not as fortunate as one. Recall that in this case more than one spindle has been assigned the same size drill bit. To help visualize the problem assume three different hole sizes are to be drilled, the Quad machine is to be used, and spindles 1 and 3 are assigned to drill hole size "a" and spindles 2 and 4 are assigned to drill size "b" and "c" respectively (see Figure 4a). Using the latter part of assumption 3, it is not known which spindle (1 or 3) should be used to drill each individual size "a" holes. What this means is that when size "a" holes are involved there are alternate costs associated with going from hole i to hole j. This condition is similar to having alternate routes (or roads) between some cities, each resulting in a different cost. However, the problem is much more complex that just choosing the minimum cost route as the value to enter into the TSP cost matrix because the cost of going to subsequent cities from the one arrived at depends directly on which route was choosen to get there: i.e., if a cost c_{ij} is choosen, the costs c_{jk} depend on c_{ij} (for all $k, k \neq i, j$). At this point the analogy to cities and alternate routes becomes much harder to visualize, therefore, it is best to return to the situation at hand.

Figure 4B is a trivial example that nevertheless illustrates the problem rather clearly. For the drilling sequence $\{1, 2, 3, 4, 1\}$ there are four possible combinations of spindle assignments: (4, 1, 1, 2, 4), (4, 1, 3, 2, 4), (4, 3, 1, 2, 4), and (4, 3, 3, 2, 4).



(a)



$$s' = \{(1|4, 2|3),\ (2|3, 3|3),\ (3|3, 4|2),\ (4|2, 1|4)\}$$

$$D_{s'} = d(1|4, 2|3) + d(2|3, 3|3) + d(3|3, 4|2) + d(4|2, 1|4)$$

$$= 4+3+5+12 = 24 \text{ inches}$$

(b)

FIG. 4. (a) TYPICAL DRILL BIT ASSIGNMENTS TO SPINDLES FOR ONE WORK STATION OF A QUAD MACHINE.

(b) ILLUSTRATION OF FOUR HOLE PROBLEM WITH ONE OF THREE OPTIMUM SOLUTIONS SHOWN.

Of these four combinations, the last one is optimum (minimum effective distance = 24 inches) and is the one shown in the figure. There are also two other drilling sequences that need to be considered - $\{1, 3, 2, 4, 1\}$ and $\{1, 3, 4, 2, 1\}$ - each resulting in four combinations of possible spindle assignments. Calculation of these eight combinations reveals that the sequence $\{1, 3, 4, 2, 1\}$ has two spindle assignment combinations that are also optimum: (4, 3, 2, 1, 4) and (4, 3, 2, 3, 4).

The problem is actually a psuedo-traveling salesman problem because it remains that each hole must be drilled (once and only once), the starting point must be returned to, and the total cycle time must be minimized. The crux of the problem is the inability to calculate a single cost matrix such that the optimum result from a TSP algorithm is indeed the optimum solution. In fact, the cost matrix cannot be calculated until each size "a" hole has been assigned a unique spindle, and the best assignment cannot be evaluated until the sequence is known. The real problem involves finding the spindle assignments (e.g. for size "a" type holes) and drilling sequence that together result in the minimum cycle time. Although Figure 4b was solved by means of exhaustive enumeration, it can be seen that this approach loses its attractiveness very quickly when large problems involving large numbers of size "a" type holes are considered. Chapter III presents a realistic, although approximate, method of solution.

CHAPTER III.

SOLUTION PROCEDURE

A. General Description and Rationale

No solution procedure for condition two has been found in the literature, therefore, a general two part heuristic algorithm was developed that is intuitively appealing and also capable of solving large problems in a reasonable amount of computer processing time. Briefly, Part I of the algorithm generates an initial drilling sequence using the Nearest-Hole-Next strategy (i.e., during the process of building the sequence, the next hole in the sequence is the nearest one). As this sequence is being built, the procedure also determines which spindle to use for those holes that can use one of several spindles (hereafter called multiple spindle holes or MSH) by selecting the spindle that results in the minimum distance from the preceding hole. The result is a complete drilling sequence that consists of a unique spindle assignment for each hole in the sequence. It should be recognized that once there is no ambiguity relative to which spindle will drill each hole, the problem is precisely the same as condition one and can therefore be optimized using a TSP algorithm. Accordingly, Part II calculates an effective distance matrix and utilizes Shen Lin's heuristic TSP algorithm to find the "optimum" or "near optimum" drilling sequence for the hole-spindle assignments made in Part I.

This approach is obviously suboptimum since no attempt is made to evaluate different hole-spindle assignments during the process of finding "optimum" drilling sequences with the TSP algorithm. However, what the approach lacks in its ability to find the true optimum hole-spindle assignments and drilling sequence, it gains in its ability to solve large problems (up to 150-200 holes) in a reasonable amount of computer time while still producing good results. If just Part I is used, the size of the problem can be increased up to 2000 holes without requiring an unreasonable amount of processing time. Reasonable computation time, as used here, refers directly to the question of whether or not manufacturing costs saved by using the algorithm will outweigh computation costs.

B. Problem Size and the TSP

The use of approximate methods is particularly justified because of the problem size considered. The TSP in itself is one of the most difficult combinatorial problems to solve and exact solution methods that can solve the problem are far from efficient, at least relative to the number of cities they can handle. Although a great deal of effort has been expended on the problem, it is generally agreed that there is still not an adequate theory for solving it efficiently (2). The difficulty stems from two factors: the number of possible tours that exist, and the requirement that a closed Hamiltonian circuit must be made that includes every city, once and only once (i.e., no subtours are allowed). Satisfying this latter requirement accounts for most of the difficulty exact algorithms encounter when searching for the optimum solution. If subtours were permitted, the well known assignment problem solution procedures would solve the problem very efficiently. The number of possible tours accounts for the explosiveness of the problem size as the number of cities increase. For asymmetrical problems ($c_{ij} \neq c_{ji}$) there are (n-1)! tours and for symmetrical problems there are $(n-1)!$ tours but only $(n-1)!/2$ tours need be considered. In either event, this knowledge is not particularly helpful for n greater than 10, but it does serve to eliminate an exhaustive enumeration approach for large problems.

A survey on the TSP by Bellmore and Nemhauser (2) presents the available theory and solution techniques that appear to be most attractive. The authors concluded that of the three solution methods they classified, Tour-to-Tour Improvement, Tour Building, and Subtour-Elimination, the Tour-to-Tour Improvement was the most feasible in terms of computation time vs. quality of solution for symmetric problems with n greater than 40. In addition, of the Tour-to-Tour Improvement methods available (which are all approximate), they recommended the use of Shen Lin's algorithm. This is one of the reasons why this algorithm was choosen for part two. Details of Lin's algorithm, and its requirement for symmetry are discussed in Section III D.

Judging from Figure 4 of the previous chapter, it is obvious that the problem size is larger than $(n-1)!/2$ (for symmetric problems). In fact the total number of possible tours and multiple hole spindle assignments is given by

$$(N-1)!/2 \prod_{i=1}^{H} (k_i)^{n_i}$$

subject to

$$\sum_{i=1}^{H} n_i = N \quad , \quad \sum_{i=1}^{H} k_i = K$$

where n_i = number of holes of size i

N = total number of holes.

H = total number of different hole sizes to be drilled.

k_i = number of spindles capable of drilling hole size i.

K = total number of spindles to be used.

For the example given in Figure 4b, this quantity is

$((4-1)!/2)\ (2)^2\ (1)^1\ (1)^1 = 12 \quad ; \ i = 1, 2, 3 \equiv a, b, c.$

Therefore for large problems, the number of different tours, coupled with the number of possible hole-spindle assignment combinations, is astronomical. Even if a true optimum seeking algorithm were available, it is doubtful that it would be efficient for the size problems considered here.

C. <u>Symmetry</u>

The question of symmetry in the cost elements has been raised several times thus far. It has also been implied that Shen Lin's algorithm is probably the best vehicle to date for solving both conditions one and two. Since the results of this thesis are meant to apply to both turret and non-turret machines, it is necessary to determine when symmetry is satisfied.

For non-turret machines, symmetry is proven below.

Assume $d(i|k, j|m) = |X_i + (SX_m - SX_k) - X_j|$

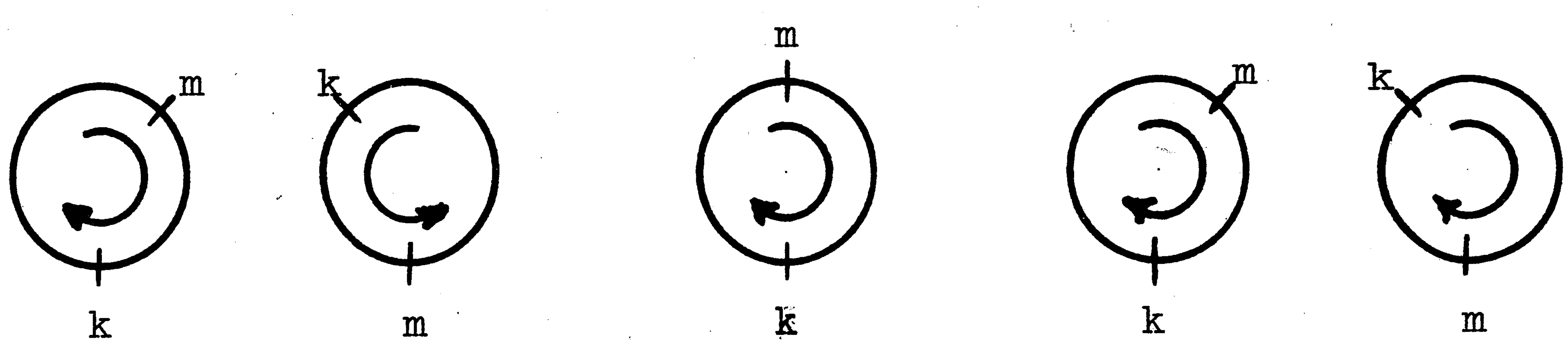
then $d(j|m, i|k) = |X_j + SX_k - SX_m - X_i|$

$$= |-X_j - SX_k + SX_m + X_i|$$

$$= d\ (i|k,\ j|m).$$

For turret machines, symmetry exists if the spindle indexing times are symmetrical: i.e. if $t_{k,m} = t_{m,k}$. This will always be true if the rotational direction is reversible. If rotational direction is not reversible, then symmetry does not exist unless the two spindles in question are located on opposite ends of the turret wheel diameter. Examination of Figure 5 reveals the reason (note that Figure 5a corresponds to reversible rotational direction and Figures 5b and 5c do not).

If symmetry does not exist, which in many cases it does not, the practitioner would be forced to use asymmetrical TSP algorithms (see reference 2) for both conditions one and two. Unfortunately, the best available algorithm for this condition is severely limited by the total number of holes that can be handled (up to approximately 70). In addition the strategy adopted to solve condition two may well be a poor one for asymmetrical problems. In any event, the reader is cautioned that symmetry may not be a valid assumption for some turret machines and consequently the results of this paper would be of questionable value for such an application.



$t_{k,m} = t_{m,k}$ (a)

$t_{k,m} = t_{m,k}$ (b)

$t_{k,m} \neq t_{m,k}$ (c)

FIG. 5. CONDITIONS UNDER WHICH TURRET SPINDLE INDEXING TIMES ARE SYMMETRICAL AND ASYMMETRICAL.

D. Detailed Description

All parts of the algorithm and mainline were programmed in FORTRAN IV and evaluated on a PDP-10 time sharing computer manufactured by the DEC Corporation. Detailed flow charts are given in Appendix A with the exception of Shen Lin's algorithm. A general step-by-step description of both parts of the algorithm, along with a detailed description of Shen Lin's algorithm is given below.

1. Input information assumed

   a. Total number of holes to be sequenced.

   b. Number of hole sizes.

c. X, Y coordinate list of all holes to be sequenced along with the corresponding hole sizes.

d. X, Y coordinates (SX, SY) of each spindle to be used.

e. Drill bit size assigned to each spindle.

II. Preliminary Processing: an array is developed from d and e above which specifies the number of spindles along with the corresponding spindle number(s) assigned to each hole size.

III. Part I: Nearest-Hole-Next Solution

Listed below is a self explanatory, step-by-step, procedure for building the initial sequence and selecting the spindles to be used to drill multiple spindle holes (MSH). Note that no selection of spindles is required if a hole size only has one spindle available for drilling.

1. Start with the first hole in the X, Y coordinate list as the first hole in the sequence. Set these coordinates to the reference coordinates. If this is a MSH, arbitrarily assign the lowest spindle number that can be used as the spindle to drill the hole.

2. Calculate the effective distance from the reference coordinates to all remaining holes. For MSH, determine the effective distance from the reference hole by calculating the distance for each spindle possible and choosing the minimum.

3. Pick the nearest hole as the next hole in the sequence and assign the spindle number to be used. If this hole is a MSH, assign the spindle number that resulted in

the minimum distance calculated in step 2 (ties are broken by arbitrarily assigning the first spindle that resulted in the minimum distance).

4. Set the reference coordinates to the hole coordinates picked in step 3.

5. Repeat steps 2 through 4 until no holes remain.

6. Calculate the distance of the completed sequence, including the link between the first and last hole.

7. Proceed to Part II.

IV. Part II: Traveling Salesman Solution

Since every hole has now been assigned a unique spindle, the symmetrical effective distance matrix is calculated (see Appendix A) and the resulting drilling sequence from Part I is used as the first initial tour for Shen Lin's TSP algorithm.

The reader is encouraged to consult reference (7) for the theory and details of Lin's algorithm, however, a brief summary of the theory and the steps actually used are repeated below for completeness. The variable names have been retained from Lin's article to allow easy cross reference.

Notation:

n = number of total holes.

d_{ij} = effective distance from hole i to hole j (effects of spindles included).

r = number of 3-opt tours desired.

t_i = i^{th} hole in the sequence.

Algorithm:

1. Do through (8), m = 1, r, 1

2. If m = 1, use the drilling sequence calculated in Part I, otherwise generate a random sequence T, $T = (t_1, t_2, \ldots, t_n)$.

3. Do through (8), count = 1, n, 1

4. Do through (7), k = 1, n-3, 1

5. Do through (7), j = k+1, n-1, 1

6. If $d_{t_k t_{j+1}} + d_{t_1 t_j} \le d_{t_k t_j} + d_{t_1 t_{j+1}}$, set d =

$$d_{t_k t_{j+1}} + d_{t_1 t_j} \text{ and } \alpha = 9 \text{, otherwise set}$$

$$d = d_{t_k t_j} + d_{t_1 t_{j+1}} \text{ and } \alpha = 11$$

7. If $d + d_{t_{k+1} t_n}$ (cost of links added) <

$$d_{t_1 t_n} + d_{t_k t_{k+1}} + d_{t_j t_{j+1}}$$ (cost of links removed) go

to α, otherwise, increment j or k, whichever is appropriate, and repeat steps (6) and (7).

8. $(t_1, t_2, \ldots, t_n) = (t_n, t_1, \ldots, t_{n-1})$, (no improvement found in steps (4) through (7), therefore rotate tour and go to step (4) if count < n, otherwise go to step (1) since one 3-opt found).

9. $(t_1, t_2, \ldots, t_n) = (t_{j+2}, \ldots, t_n, t_{k+1}, \ldots,$

$t_j, t_1, \ldots, t_k, t_{j+1})$ (links exchanged and tour perturbed).

10. Go to step (3) (treat improved tour as initial tour).

11. $(t_1, t_2, \ldots, t_n) = (t_{j+2}, \ldots, t_n, t_{k+1}, \ldots, t_j, t_k, \ldots, t_1, t_{j+1})$ (links exchanged and tour perturbed).

12. Go to step (3) (treat improved tour as initial tour).

Summary:

The following is a brief summary of what the algorithm actually does. As indicated before, Lin's algorithm is of the Tour-to-Tour Improvement type. In its original form, a random tour is generated and it is checked for improvement by comparing the sum of the distances or links between 3 pairs of cities with the sum of the links between 3 reference pairs of cities in the tour. If the first sum is less than the second sum (step (7)), then the tour is improved by exchanging the links of the first sum with that of the reference links according to step (9) or (11). Note in step (6) that actually two sets of 3 links are compared before comparing the lesser sum with that of the reference links in step (7). Step (6) then, keeps a record of whether step (9) or (11) is to be used for the exchanging of links. This whole process is shown schematically below:

Initial Tour T

$t_1, t_2, \ldots, t_k, t_{k+1}, \ldots, t_j, t_{j+1}, \ldots, t_n$

reference links

Step (9) interchange (determined by step (6))

if $d_{t_k t_{j+1}} + d_{t_1 t_j} + d_{t_{k+1} t_n} < d_{t_1 t_n} + d_{t_k t_{k+1}} + d_{t_j t_{j+1}}$ (step (7))

then

$t_1, t_2, \ldots, t_k, t_{k+1}, \ldots, t_j, , t_{j+1}, t_{j+2}, \ldots, t_n$ (step (9))

and $T = T' = t_{j+2}, \ldots, t_n, t_{k+1}, \ldots, t_j, t_1, t_2, \ldots, t_k, t_{j+1} =$

$t'_1, \ldots, t'_n$

Note that the section $t_1, \ldots, t_k$ has been inserted as is between holes t_j and t_{j+1}, and that the tour has been rotated by placing the section $t_{j+2}, \ldots, t_n$ at the front of the sequence.

Step (11) interchange (determined by step (6))

if $d_{t_k t_j} + d_{t_1 t_{j+1}} + d_{t_{k+1} t_n} < d_{t_1 t_n} + d_{t_k t_{k+1}} + d_{t_j t_{j+1}}$ (step (7))

then

$\{t_k, t_{k-1}, \ldots, t_2, t_1\}$

$t_1, t_2, \ldots, t_k, t_{k+1}, \ldots, t_j, , t_{j+1}, t_{j+2}, \ldots, t_n$ (step (11)) and $T = T' = t_{j+2}, \dots , t_n, t_{k+1}, \dots , t_j, t_k, t_{k-1}, \dots ,$

$$t_2, t_1, t_{j+1} = t_1', \dots , t_n'$$

Note here that the section $t_1, \dots , t_k$ has first been inverted before insertion between holes t_j and t_{j+1} which is the only difference from step (9). Note also that inverting a section requires that the problem be symmetrical in the distance measurements otherwise the change made would not guarantee that the only change in the total sequence distance would be the difference between the sum of the two sets of links interchanged.

The above procedure is terminated when no further exchange of 3 links can be made that will reduce the total sequence distance of the tour T (see reference 7). When this occurs, the tour is said to be 3-optimal and the result is considered by Lin to be one 3-opt tour. A new random sequence is then generated and the entire algorithm is reiterated to form other 3-opt tours. After r, 3-opt tours have been generated, the best 3-opt tour is selected as the solution to the problem.

The steps of the algorithm given are not all the ones specified by Lin. Lin also employes a reduction scheme that was not used in this application. The scheme requires the generation of many 3-opt tours (say 10) from which the common links of all the 3-opt tours are removed. This effectively reduces the number of cities that must be evaluated on subsequent 3-opt tours. The reason this scheme was not adopted was because the number of 3-opt tours needed to use it would require more computer time than was considered necessary for the thesis. The actual computation time required for a 3-opt tour is covered in subsequent chapters.

CHAPTER IV.

EXPERIMENTAL DESIGN

A. General

The method of evaluating the generality and effectiveness of the algorithm was structured so that answers to the following questions could be found.

1. In terms of the total effective travel distance resulting from the use of the algorithm, does it make any difference which machine (QUAD or IN-LINE) is used?
2. Does it make any difference how the drill bit sizes are arranged in the spindles?
3. How does the area (size of the PWB), total number of holes sequenced, number of hole sizes, and number of MSH affect the outcome of Parts I and II of the algorithm?
4. How bad is the practice of drilling in the sequence of ascending X, Y coordinates if this were done in a system like CAPP?
5. For Part II of the algorithm, what results can be expected if more than one, 3-opt tour is generated?
6. On the average, how much computation time is required to obtain a solution from each part of the algorithm?

In order to answer these questions a designed experiment approach was taken where probable extremes were selected for the factors mentioned in (2) and (3). These factors were in turn used to generate simulated problems which were then solved for both the QUAD and IN-LINE machines. An explanation of these factors and the extremes chosen is given below.

B. Factors Considered in the Experiment

1. Drilling Area (A)

For this factor, no experimental data is actually necessary to confirm that the total expected travel distance of the drilling sequence will increase as the area or size of the PWB increases. This follows from assuming that the holes and hole sizes are uniformly and randomly distributed over the PWB area, and that, for the same number and relative location of holes, an increase in area simply increases the relative distance between holes.* Nevertheless, it was still of interest to determine how the travel distance changes as area changes. Two areas were selected for evaluation.

a. The large area was set to 280 square inches which corresponds to a 20x14 inch PWB (X=20", Y=14"). This is approximately the largest drilling area the two sixteen spindle machines can drill per work station.

b. The small area was set to 24 sq. in. which corresponds to 6x4 inch PWB. One reason for the particular dimensions choosen was that a 2 inch spacing between spindles (which was assumed for both machines) results in a 6 inch spacing between the first and last spindle for the IN-LINE machine. Consequently,

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*This further implies that the same drilling sequence would be found for large and small areas and that, in general, the ratio of width to length of the PWB remains constant as the area is increased. More will be said about the distribution of holes in the problem generation section.

it was felt that this was a reasonable limitation on the length of a PWB that would be drilled by this machine (although technically, the machine is not limited to this).

2. Total Number of Holes (N)

This factor severely limited the amount of experimental data that could be gathered due to the amount of computer processing (CPU) time required to obtain a solution with Lin's algorithm. Lin estimated the expected time required to generate one 3-opt tour to be $30N^3x10^{-6}$ seconds. When coded in FORTRAN IV, and based on preliminary runs and results reported in reference (9), this time was found to be approximately an order of magnitude higher, or, somewhere between $30N^3x10^{-5}$ and $50N^3x10^{-5}$ seconds. Therefore, to generate just one, 3-opt tour it would require approximately 6-1/2 minutes for a 100 hole problem and 30 minutes for a 160 hole problem. As a result of this estimate and in an effort to conserve CPU time required for the thesis, the upper limit was set at 160 holes.

As with the area factor, it can be reasoned that total travel distance increases as the number of holes increases, however, it was still of interest to determine how the travel distance was affected as the number of holes varied. Therefore three levels were chosen.

a. A lower level of 40 holes was considered a reasonable lower limit since most multiple hole size drilling operations involve at least this many in practice.

b. The intermediate level was set at 100 holes.

c. The upper limit was set at 160 holes for reasons already mentioned.

3. Number of Hole Sizes to be Drilled (H)

For the two machines considered, the number of hole sizes can vary between one and four. In addition, it is necessary to utilize all four spindles in order to have the condition where more than one spindle is able to drill the same size hole. Since the four hole size problem does not allow for MSH, it was eliminated from consideration. For the one hole size case, it can be reasoned that a single spindle machine would more than likely be used in this situation since no setup cost advantages could be gained by using a multiple spindle machine, consequently, this case was also eliminated. Therefore, only the two and three hole size problems were considered.

a. In the two hole size case two conditions are possible: three spindles could be assigned to drill one hole size and the remaining spindle assigned to drill the other, or, each hole size could be assigned two spindles. This latter condition was chosen since it appears more likely to occur in practice and further because it would provide the condition where all holes were MSH.

b. In the three hole size case, two spindles were assigned to the hole size with the most number of holes, and one spindle each was assigned to the other two hole sizes.

4. Number of Multiple Spindle Holes (M)

This factor was controlled to test the hypothesis that an increase in the number of MSH results in a decrease in the total travel distance. This factor is more meaningful for the three hole size case since it was used as a criteria for assigning multiple spindles to hole sizes, however, it was still considered a variable for the two hole size case during data analyzation.

The levels of this factor are designated as a fraction (F) of the total number of holes and were used to determine the number of holes/hole size in the three hole size case. Three levels were chosen.

a. Three hole size case ($.34N \leq M < N$)

(1) $F = .34$ or $M = .34N$: a lower limit of 34% of N was selected for the number of MSH, with the other 66% split evenly among the remaining two hole sizes (i.e., the number of holes/hole size is approximately equal for all three hole sizes).

(2) $F = .9$ or $M = .9N$: an upper limit of 90% of N was selected for the number of MSH, with the remaining 10% split evenly among the remaining two hole sizes.

b. Two hole size case ($F=1$ or $M=N$): in this case, all of the holes are MSH, however, for the purpose of problem generation, the number of holes/hole size was set equal to .5N each.

5. Arrangement of Drill Bits in the Spindles (P)

For this factor, there are 6 and 12 possible ways of permuting the drill bit sizes in the spindles for the two and three hole size cases respectively. Of these 6 and 12 arrangements only two are statistically different for the QUAD machine and only three are statistically different for the IN-LINE machine. The actual arrangements used are shown schematically in Figure 6.

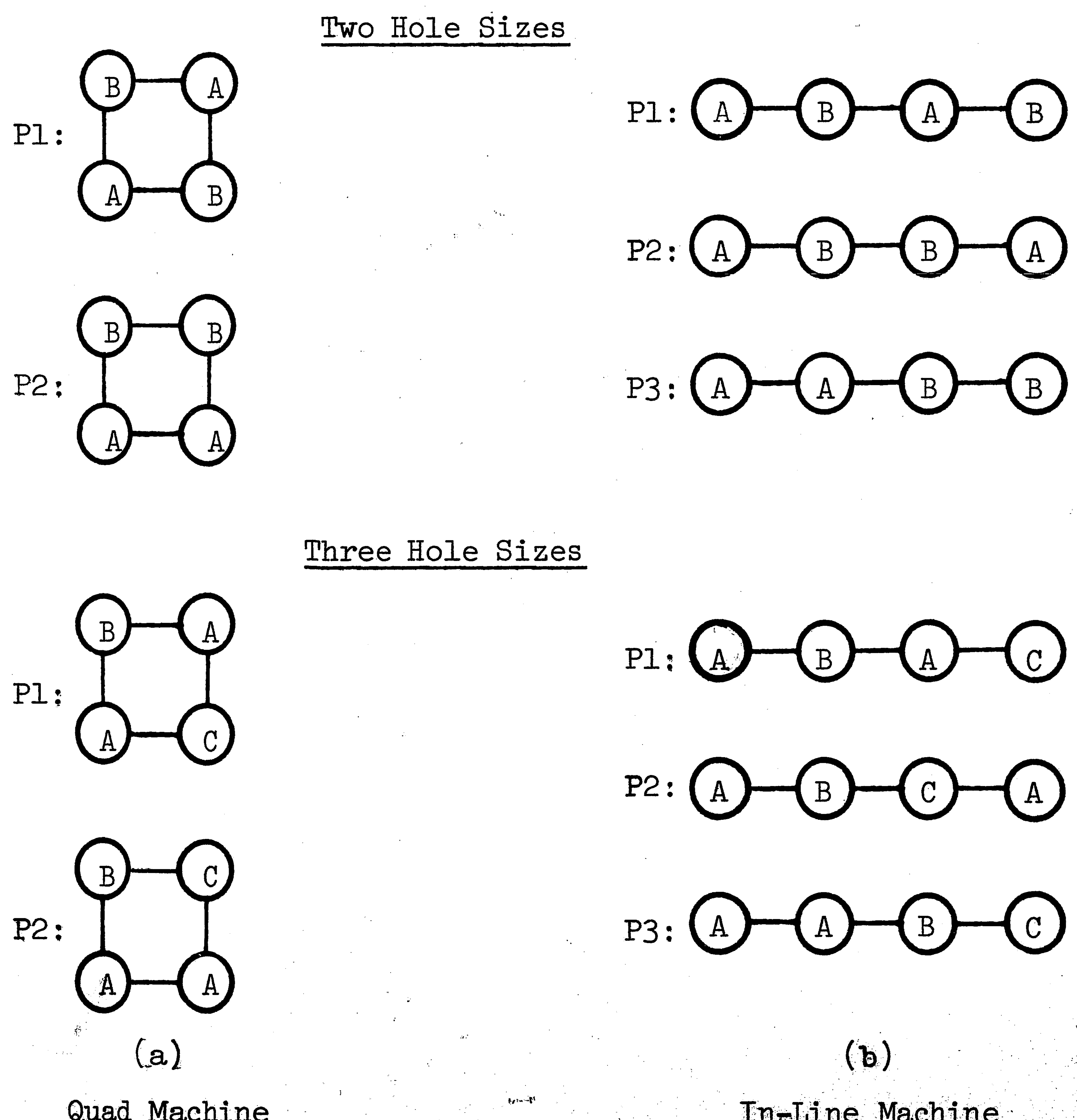

FIG. 6. DRILL BIT ARRANGEMENTS TESTED FOR THE QUAD AND IN-LINE MACHINES.

6. Number of 3-opt Tours

The question of how many 3-opt tours to generate is a difficult one to evaluate particularly in view of the CPU time required for each tour (see 2 above). Technically, the probability of obtaining "the optimum" solution could be set, to say .99, and the number of tours required could then be calculated to meet this objective. Using Lin's estimate of the probability that a 3-opt tour is optimum, a 100 hole problem would require 300, 3-opt tours in order to insure a .99 probability that at least one tour would be optimum. The method of calculation is shown in reference (7) and will not be repeated here.

Obviously this approach is not very practical for the type of application considered here. While this criteria is theoretically important, it does not provide any information on how close to optimum a 3-opt tour is likely to be. Therefore, it was decided to generate ten, 3-opt tours for three preliminary problems, consisting of 30, 60, and 100 holes in order to see if any significant reductions in travel distance occurred. For the problems tested, the differences between the first and tenth 3-opt tour were 1.605, 0.098, and 1.699 inches for the 30, 60, and 100 hole problems respectively, and these improvements occurred within the first three 3-opt tours.*

*All three problems were based on the large PWB (area = 280 sq. in.).

The conclusion drawn from this data was that it would not be reasonable to generate more than three 3-opt tours for the purposes of the thesis since the improvements made were insignificant compared to the amount of CPU time required. It was decided, however, to generate three 3-opt tours per problem solved to determine if a larger sample of problems revealed any significant gains over the first 3-opt tour.

C. Method of Problem Generation

The philosophy taken for problem generation was that, in general, the layout of holes on a PWB is uniformly and randomly distributed over the area. One could take issue to this statement on the grounds that hole patterns almost always appear on real PWB designs and that their existence invalidates such an assumption. While this is true, no particular gains in reality could be expected by generating problems with known patterns since these patterns continually change as new technology devices are developed and used. Therefore, it was felt that a rather wide range of possible designs could be simulated by generating problems whose holes and hole sizes were uniformly and randomly distributed over the area.

To generate the problems to be solved by the algorithm, a problem generator was developed that provides an ascending X, Y coordinate list of holes and hole sizes for the conditions dictated by the area (or PWB dimensions), number of total holes, number of hole sizes, and number of holes/hole size. A detailed flow chart of the generator is shown in Appendix A and a general step by step description is given below.

1. Read in Input Parameters;

   a. Dimensions of PWB to be simulated (20"x14" or 6"x4").

   b. Total number of holes (40, 60, or 160).

   c. Number of hole sizes (3 or 2).

   d. Fraction of total number of holes/hole size, MSH first (.34, .33, .33; .9, .05, .05; or .5, .5).

   e. Initial random number generator seed.

2. Calculate random X, Y coordinates for each hole by multiplying each PWB dimension by a random number between zero and one (two uniform random numbers per hole).

3. Calculate the number of holes/hole size (e.g. $n_1 = .34N$, $n_2 = .33N$, $n_3 = .33N$, where n_i = number of holes/hole size i).

4. Assign hole sizes to the hole locations calculated in step 2 (e.g., assign first n_1 holes, hole size 1, next n_2 holes size 2, etc.).

5. Sort the hole coordinates by ascending X, Y coordinates.

6. Output the hole coordinate list and corresponding hole sizes.

D. Experimental Procedure

There were actually two experiments carried out; one for the QUAD machine and one for the IN-LINE. In addition, the two and three hole size cases were split into two experiments within the machine experiment with one observation taken for each combination of different factor levels.

Because of the large amount of CPU time required for the 160 hole problem, it was decided to run the experiment in two phases. The first phase consisted of only 40 and 100 hole problems with one observation per combination of factor levels. The objective for this phase was to determine if any significant differences existed between the arrangement of the drill bits in the spindles and if any significant reduction in tour length resulted by generating three, 3-opt tours. The results of this phase were then analyzed to determine if there was any reason to continue data collection for all levels of drill bit arrangements and whether or not it would be necessary to generate three, 3-opt tours at the 160 hole level. Therefore, phase II consited of gathering data at the 160 hole level based on the decisions made at the end of phase I. The design for phase I is summarized below:

Notation

A = area of PWB (24 and 280 sq. inches)

N = total number of holes (40 and 100)

F = fraction of N that are MSH (.34, .9, and 1)

P = different arrangements of drill bits

LEVELS OF FACTORS

FACTOR	2 Hole Sizes QUAD	2 Hole Sizes IN-LINE	3 Hole Sizes QUAD	3 Hole Sizes IN-LINE
A	2	2	2	2
N	2	2	2	2
F	1	1	2	2
P	2	3	2	3
No. of Obs.	8	12	16	24

Reference to appendix B, where the tabular layout of both phases is shown, will further clarify the design structure.

The method of data collection for phase I was performed in the following manner: a problem would be generated for the particular levels of factors desired (e.g. 3 hole sizes, A = 24 sq. in., N = 40, and F = .34); next, the same problem would be solved for both machines using each level of arrangement of the drill bits in spindles. This procedure was adopted in order to provide a better comparison between the two machines and the drill bit arrangements within machines. As a result of this procedure, twelve different problems were required for phase I with an additional six different problems for phase II. The number in the upper left hand corner of the observation blocks in the tables of appendix B represents the problem number solved to obtain the response shown.

The actual data collected for each problem solved consisted of:

1. CPU time required for Parts I and II of the algorithm.
2. Total effective travel distance, in inches, for the bench mark rule (defined below).
3. Total effective travel distance, in inches, for the drilling sequence calculated in Part I of the algorithm.
4. Total effective travel distance, in inches, for the drilling sequence calculated in Part II of the algorithm 3-opt tour generated.

The bench mark distance is the total effective travel distance required when the holes are drilled in the sequence of ascending X,Y coordinates and the MSH holes are randomly assigned spindles. A detailed flow chart for calculating this distance is shown in appendix A. Recall from Chapter II that this method of drilling would be adopted in CAPP if the output from the graphics program provided the input to CAPP and if no attempt were made to find a better drilling sequence. Since this is a possibility, it was felt that this distance would provide a reasonable frame of reference for evaluating the algorithm.

CHAPTER V.

EMPIRICAL RESULTS AND ANALYSIS

A. General

The results obtained for both phases of the experiment are tabulated in Appendix B for the QUAD and IN-LINE machines in the order of (1) Bench Mark travel distance, (2) total effective travel distance resulting from the drilling sequence found in Part I of the algorithm (Nearest-Hole-Next), and (3) total effective travel distance resulting from the drilling sequence found by the first 3-opt tour of Part II of the algorithm (Traveling Salesman Solution). In the analysis that follows, the distinction between the 2 hole size and 3 hole size experiments has been dropped, and all the data was analyzed together.

B. Phase I Results

1. Evaluation of number of 3-opt tours

At the end of phase I of the data collection (40 and 100 hole problems only), the effect of the number of 3-opt tours was evaluated to determine if any significant reductions in total travel distance occurred between the first and the third 3-opt tour generated. The differences between the first and third 3-opt tour, in inches, are summarized in table 1 in the form of a tabulated histogram. The data was split into small and large areas since, when improvements were made over the first 3-opt tour, the magnitude of these changes were significantly higher for the larger area. In general this will be the case, i.e., the larger the area the larger the improvements will be as additional 3-opt tours are generated.

Table 1. Tabulated Histogram of differences between the 1st and 3rd, 3-opt tours (40 and 100 hole problems)

Magnitude (inches)	Frequency Small Area ($24\ in^2$)	Large Area ($280\ in^2$)	Combined
no change	11	14	25
*0.000-0.500	23	19	42
0.501-1.000	6	1	7
1.001-1.500	1	1	2
1.501-2.000	0	1	1
2.001-2.500	0	0	0
2.501-3.000	0	2	2
3.001-3.500	0	1	1
3.501-4.000	0	1	1
4.001-4.500	0	2	2
4.501-5.000	0	2	2
Mean :	0.280	1.135	0.707
Std. Dev. :	0.362	1.645	1.257

*includes number of times there was no change.

It can be seen from table 1 (combined case) that in nearly half (25) of the observations (60) there was no change at all. In addition, the magnitude of the changes were quite small as shown by the means under each column (the maximum decrease in travel distance was 4.613 inches). From a practical standpoint, especially when compared to the CPU time required per 3-opt tour, these small changes do not appear to justify the generation of more than one 3-opt tour. It can also be concluded that one 3-opt tour will probably be very close to the optimum solution for a given TSP. Of course the decision to generate additional 3-opt tours in practice should be based on whether or not manufacturing costs saved will offset the computation costs required. In any event, it was decided not to generate more than one 3-opt tour, for the 160 hole problems and to only analyze the results for the first 3-opt tour.

2. Evaluation of Different Arrangements

To determine whether or not additional data would be required for the arrangement factor at the 160 hole level, a one sample t-test was performed. The procedure was to take a pairwise difference between the responses (denoted by X_i) for each arrangement tested at each combination of the other factor levels. The mean and standard deviation of the differences were then computed and a "t" statistic calculated using the formula

$$t = \frac{(\overline{X} - \mu)\sqrt{n}}{S} \qquad \text{and } S^2 = \sum_i (X_i - \overline{X})^2/(n-1)$$

where n = number of differences

$\mu = 0$

Since the variance varied significantly with the levels of the other factors, a transformation of the data was found that stabilized this variation. The transformation used was the cube root of all the responses for both machines. The null hypothesis tested was that the mean of the differences between any two arrangements was equal to zero. The hypothesis was rejected if $|t| > t_{(\alpha/2,\ n-1)}$, where α represents the area in the critical region of rejection for the t distribution and is the probability of rejecting the hypothesis when it is true. An α of .05, corresponding to a .05 level of significance, was chosen.

The results of this test for both parts of the algorithm, are tabulated in table 2. Note that the means shown are the means of the difference of the transformed responses, and that these differences include both the two and three hole size results.

Table 2. Phase I Results (40 and 100 hole problems)-Comparison between drill bit arrangements.

		QUAD MACHINE			
		PART I		PART II	
Arrangements	D.F.	$\lvert t \rvert$	$\bar{X}$	$\lvert t \rvert$	$\bar{X}$
P1-P2	11	1.603	-0.0637	1.270	-0.0324
		IN-LINE MACHINE			
P1-P2	11	0.606	-0.0037	12.134*	-0.0297
P2-P3	11	4.071*	-0.0361	10.383*	-0.0424
P1-P3	11	2.743*	-0.0398	8.905*	-0.0721

*significant at the 5% level

Since there was no significant difference between the arrangements of the QUAD machine, this factor was dropped from evaluation at the 160 hole level, however, both the P1 and P2 arrangements were used to obtain the additional observations shown in Appendix B since there is no reason to believe one is better than the other.

Since there was a significant difference between all combinations of the arrangements in the IN-LINE machine, except for P1-P2 using part I, it was decided to retain this factor for all three levels at the 160 hole level and then to rerun the t-test. This factor was only retained for the small area since it was reasoned that no additional information could be gained by taking more observations at another level of area. In addition, since P1 appeared to be a better arrangement than either P2 or P3, the additional data would provide a better comparison in terms of the average percent increase in travel distance that could be expected if P2 or P3 were used instead of P1.

C. Phase II Results

1. Final Evaluation of Arrangements--IN-LINE Machine.

The results of the t-test when the 160 hole observations are included is tabulated below. Note that these results do not include the observations at the large area level.

Table 3. Comparison between Drill Bit Arrangements for the IN-LINE Machine (40, 100, and 160 Hole Problems)

		PART I		PART II	
Arrangements	D.F.	$\lvert t \rvert$	$\bar{X}$	$\lvert t \rvert$	$\bar{X}$
P1-P2	14	3.786*	-0.0253	17.577*	-0.0497
P2-P3	14	2.611*	-0.0189	6.005*	-0.0208
P1-P3	14	4.200*	-0.0442	11.744*	-0.0706

*significant at the 5% level.

These results show an even sharper difference between the three arrangements tested, and it is concluded that arrangement P1 is better (results in the smallest travel distance) than either P2 and P3, and that P2 is better than P3 for both parts of the algorithm.

Since there may be criteria other than minimum total travel distance for choosing a particular drill bit arrangement, the average percent increase that can be expected if P2 or P3 is used instead of P1, is tabulated below for both parts of the algorithm. The quantities shown were computed by dividing the difference of the means of P1 and P2 or P3 by the mean of P1 and multiplying by 100. The averages used were for the actual responses (i.e. nontransformed) and excluded the responses shown for the large area at 160 holes.

Table 4. Percent average increase in total travel distance over arrangement P1.

Arrangement	PART I	PART II
P2	1.30%	2.94%
P3	3.75%	5.74%

2. Evaluation of Computation Time

This section summarizes the amount of CPU time required to obtain a solution for each part of the algorithm. Predictive equations were developed using multiple linear regression, however, their usefulness is limited to comparisons between the two parts of the algorithm or for predicting CPU time when the algorithm is used on the PDP-10 computer.

a. Part I

The CPU time required for this part of the algorithm is a function of the total number of holes, number of MSH, and number of spindles assigned to the MSH. Since this latter factor was a constant in the experiment (2 spindles/MSH) it is not considered in the predictive equation. The equation developed is shown below.

Letting t_I = CPU time for Part I

N = total number of holes

M = number of multiple spindle holes ($.34N \leq M \leq N$)

$= FN$

$$t_I = (12.4N^2 + 8.6M^2) \times 10^{-5} \text{ seconds}$$

Using this equation, the times required for solution are tabulated below:

Table 5. Predicted CPU time, in seconds, for Part I of the algorithm.

	F(Fraction of N that are MSH)		
N	.34	.90	1.0
40	0.215	0.310	0.336
100	1.343	1.938	2.102
160	3.438	4.963	5.380

b. Part II

Since there was a rather large variation of solution times for part II, average values were computed for each level of N used in the experiment. The values tabulated below are for the first 3-opt tour only (all values in seconds).

Table 6. Average CPU Times, in seconds, required to generate the first 3-opt tour for different levels of N.

N	Average CPU Time	Std. Dev.	Minimum	Maximum
40	14.9	3.81	7.0	24.8
100	372.2	101.54	193.3	598.6
160	1972.1	515.37	1279.4	3266.0

An estimate of the CPU time /3-opt tour in seconds is given by

$$t_{II} = 47N^3 \times 10^{-5} \text{ seconds}$$

As can be seen by these results, the time to generate a solution using Part I is negligible compared to Part II. This fact should have considerable influence on deciding whether the reduction in travel distance resulting from Part II will justify the expenditure of such large amounts of CPU time when used on real problems.

3. Predictive Equations--Total expected travel distance

In order to analyze the effects that the factors have on the outcome of both parts of the algorithm, multiple regression models were fitted to the data shown in Appendix B. The four models developed and the summary of the regression results are shown in tables 7 through 10. In general, all models account for at least 98% of the variation in the data and all the F ratios due to regression are highly significant. A discussion of the models for each machine is given below.

a. QUAD machine models

The regression variable found to account for most of the variation in the data for both machines and for both parts of the algorithm was $\sqrt{(AN)}$. Webb (11) makes reference to a deduction by Beardwood, et al (1) that indicates the expected length of the optimal TSP solution is proportional to $\sqrt{(AN)}$. Therefore, the inclusion of this variable and the variable (N/A) can be considered as density measurements of the number of total holes in a given area. The inclusion of (M), the number of MSH, confirms that the total travel distance does decrease as the number of MSH increases and verifies that it is best to assign multiple spindles to the hole size that has the most number of holes.

Tables 11 and 12 summarize the travel distances predicted by models 1 and 2 respectively and given an indication of the magnitude of change in total travel distance that can be expected for different combinations of area, total number of holes, and levels of MSH. It can be seen from these tables, that in general, the total travel distance can be expected to increase as the area and number of holes increase and decrease as the number of MSH approaches the

Table 7. Summary of Regression results for Model 1: Total travel distance using Part I of the algorithm for the QUAD machine.

$$D = -5.1743 + 0.9675\sqrt{(AN)} - 0.25966(M) + 5.4974(N/A)$$

$\overline{D}$ = 83.506 inches

Variable	Coefficient	Std. Error of Coeff.
$\sqrt{(AN)}$	0.96750	0.03070
M	5.49742	0.89460
N/A	-0.25966	0.03753

ANALYSIS OF VARIANCE

Source of Variation	Sums of Sq.	D.F.	Mean Sq.	F-Ratio
Due to Regression	73849.9850	3	24616.6620	666.21
Due to Residual	960.7140	26	36.9506	
Total	74810.6990	29	2579.6793	

Multiple Correlation Coefficient Squared = .9872

Table 8. Summary of Regression results for Model 2: Total travel distance using Part I and Part II of the algorithm for the QUAD machine.

$$D = -0.5267 + 0.7546\sqrt{(AN)} - 0.1680(M) + 3.3892(N/A)$$

$\overline{D}$ = 69.1179 inches

Variable	Coefficient	Std. Error of Coeff.
$\sqrt{(AN)}$	0.75457	0.01625
M	-0.16799	0.01986
N/A	3.38920	0.47338

ANALYSIS OF VARIANCE

Source of Variation	Sums of Sq.	D.F.	Mean Sq.	F-Ratio
Due to Regression	48278.4714	3	16092.8230	1555.41
Due to Residual	269.0046	26	10.3463	
Total	48547.4760	29	1674.0509	

Multiple Correlation Coefficient Squared = .9945

Table 9. Summary of Regression results for Model 3: Total travel distance using Part I of the algorithm for the IN-LINE machine.

$$D = 10.2576 - 0.0551(A) - 13.7614(F) + 1.0266\sqrt{(AN)} - 0.00058(AFN)$$

$$\overline{D} = 81.3454 \text{ inches}$$

Variable	Coefficient	Std. Error of Coeff.
A	-0.05509	0.01594
F	-13.76141	4.30019
$\sqrt{(AN)}$	1.02657	0.05709
AFN	-0.00058	0.00025

ANALYSIS OF VARIANCE

Source of Variation	Sums of Sq.	D.F.	Mean Sq.	F. Ratio
Due to Regression	72986.3350	4	18246.5840	624.91
Due to Residual	788.3610	27	29.1986	
Total	73774.6960	31	2379.8289	

Multiple Correlation Coefficient Squared = .9893

Table 10. Summary of Regression results for Model 4: Total travel distance using Part I and Part II of the algorithm for the IN-LINE machine.

$$D = 0.2406 + 0.7760\sqrt{(AN)} - 0.0806(M) + 1.9246(N/A) - 0.00043(AFN)$$

$\overline{D} = 66.6850$ inches

Variable	Coefficient	Std. Error of Coeff.
$\sqrt{(AN)}$	0.77600	0.02801
M	-0.08602	0.03447
N/A	1.92459	0.68195
AFN	-0.00043	0.00020

ANALYSIS OF VARIANCE

Source of Variation	Sums of Sq.	D.F.	Mean Sq.	F. Ratio
Due to Regression	44735.9665	4	11183.9920	602.01
Due to Residual	501.6005	27	18.5778	
Total	45237.5670	31	1459.2763	

Multiple Correlation Coefficient Squared = .9889

Table 11. Predicted values of Model 1 for combinations of area, number of holes, and number of MSH (expressed as a fraction of N).

		Small Area (24 in^2)			Large Area (280 in^2)		
F	N =	40	100	160	40	100	160
.34:		30.332	56.303	77.410	94.367	149.854	188.724
.90:		24.619	41.762	54.041	88.655	135.313	165.355
1.00:		23.581	39.166	49.886	87.616	132.716	161.201

Table 12. Predicted values of Model 2 for combinations of area, number of holes, and number of MSH (expressed as a fraction of N).

		Small Area (24 in^2)			Large Area (280 in^2)		
F	N =	40	100	160	40	100	160
.34:		26.151	44.851	59.757	77.463	121.236	152.050
.90:		22.455	35.444	44.638	73.767	111.828	136.931
1.00:		21.783	33.764	41.950	73.095	110.149	134.243

total number of holes.

b. IN-LINE machine models

The data used to develop models 3 and 4 consisted of the observations for arrangements P1 and P2 only. The data for arrangement P3 was not included since it was the worst arrangement of the three. Additionally, the observations for the 2 hole size problem at the 160 hole and large area levels was eliminated since it was found to be an extreme outlyer compared to the rest of the data. Even though an assignable reason could not be found for excluding this value, its influence on the total variation of the data was so large that its elimination was judged reasonable.

Essentially, the same variables came into regression as in the QUAD machine models (i.e. $\sqrt{(AN)}$ and F or M), however, the inclusion of the higher order interaction (AFN) does indicate a difference between the two machines. It is speculated that a relationship exists between the spacing of the spindles and the length of a PWB to be drilled. Recall that the distance between the first and last spindle for this machine is the same as the length of the PWB simulated for the small area, and therefore it appears that the spindle configuration may become a significant variable for small boards and become less significant as PWB length increases. Since intermediate values of area were not included in the experiment, this hypothesis could not be evaluated, and hence is only mentioned as a possible area for future study.

The same general comments made relative to the effects of the factors on total travel distance for the QUAD machine applies also to the IN-LINE machine models. Tables 13 and 14 summarize the predicted values for the different levels of the factors.

c. Magnitude of difference between Part I and II of the algorithm.

Tables 15 and 16 summarize the expected reduction in travel distance due to Part II, for the QUAD and IN-LINE machines respectively. It can be seen that, in general, larger reductions in travel distance occur when the area and total number of holes increase, and as the number of MSH decrease. These tables may be helpful in deciding whether or not to use the second part of the algorithm for a particular application. Of course, the values shown are the "expected" reductions and give no indication of the variations involved.

4. Evaluation of the Bench Mark Distance

Table 17 (a) and (b) indicates the average savings, in inches, that resulted between Part I of the algorithm and the Bench Mark rule for both machines. It can be seen that the Bench Mark distance is improved upon considerably even if just Part I of the algorithm is used. From the viewpoint of the percent savings involved, the lowest percent savings that occurred was 53% and the largest was 90%. The overall average percent savings was approximately 70%. The conclusion to be drawn here is that the rule of

Table 13. Predicted values of Model 3 for combinations of area, number of holes, and number of MSH (expressed as a fraction of N).

F	N =	Small Area (24 in^2) 40	100	160	Large Area (280 in^2) 40	100	160
.34:		35.876	54.079	67.120	96.605	156.457	198.678
.90:		27.861	45.600	58.177	85.292	139.734	176.545
1.00:		26.429	44.086	56.581	83.272	136.748	172.371

Table 14. Predicted values of Model 4 for combinations of area, number of holes, and number of MSH (expressed as a fraction of N).

F	N =	Small Area (24 in^2) 40	100	160	Large Area (280 in^2) 40	100	160
.34:		26.225	43.188	56.249	79.887	123.975	154.736
.90:		24.222	38.099	48.075	75.438	112.771	136.777
1.00:		23.858	37.191	46.621	74.637	110.770	133.425

Table 15. Predicted reductions in travel distance expected by using Part II of the algorithm (Model 1-Model 2) for combinations of area, number of holes, and number of MSH (expressed as a fraction of N).

F	N =	Small Area (24 in^2)			Large Area (280 in^2)		
		40	100	160	40	100	160
.34:		4.1	11.4	17.6	16.9	28.7	36.6
.90:		2.1	6.4	9.4	14.9	23.5	28.5
1.00:		1.8	5.4	7.9	14.5	22.5	27.0

Table 16. Predicted reduction in travel distance expected by using Part II of the algorithm (Model 3-Model 4) for combinations of area, number of holes, and number of MSH (expressed as a fraction of N).

F	N =	Small Area (24 in^2)			Large Area (280 in^2)		
		40	100	160	40	100	160
.34:		9.7	10.9	10.9	16.7	32.5	44.0
.90:		3.7	7.5	10.1	9.9	26.9	39.8
1.00:		2.5	6.9	10.0	8.7	25.9	38.9

Table 17. Magnitude of difference, in inches, between average Bench Mark Distance and average travel distance from Part I of the algorithm for (a) QUAD machine and (b) IN-LINE machine.

(a)

N	Small Area (24 in^2)	Large Area (280 in^2)
40	56.7	116.5
100	160.9	368.8
160	277.1	589.2

(b)

N	Small Area (24 in^2)	Large Area (280 in^2)
40	84.0	130.3
100	239.8	392.3
160	391.0	680.3

drilling in ascending X, Y coordinates is an extremely poor one and at the very least Part I of the algorithm should be used to find a better drilling sequence.

5. Evaluation of the Difference Between Machines

To test if any significant difference exists between machines in terms of travel distance obtained when the algorithm is used, a difference of means t-test was performed. The t statistic used is calculated by the formula

$$t = \frac{\bar{D}_1 - \bar{D}_2}{\sqrt{\left\{\frac{(N_1-1)\, S_1^2 + (N_2-1)\, S_2^2}{N_1+N_2-2}\right\}}\sqrt{\left\{\frac{1}{N_1}+\frac{1}{N_2}\right\}}}, \text{with } N_1+N_2-2 \text{ d.f.}$$

where $\bar{D}_1$ = average travel distance for the QUAD machine

$\bar{D}_2$ = average travel distance for the IN-LINE machine

N_1 = number of observations taken for the QUAD machine = 30

N_2 = number of observations taken for the IN-LINE machine = 32

In order to make a meaningful test for the difference between the means of the two machines, the variation due to the common factors (area, number of holes, etc.) should be removed from the sample variance. Since the regression models developed effectively do this, the residual mean squares of the models were used as estimates of the sample variances S_1^2 and S_2^2. A .05 level of significance was chosen to reject the null hypothesis that $\overline{D}_1 = \overline{D}_2$. The results are summarized below.

Table 18. Comparison between the means of the QUAD and IN-LINE machines for each part of the algorithm.

	$\overline{D}_1 - \overline{D}_2$	$\hat{S}_1^2$	$\hat{S}_2^2$	d.f.	t
Part I	2.1608	36.9506	29.1986	60	1.481
Part II	2.4329	10.3463	18.5778	60	2.506*

*significant at the 5% level.

The conclusion drawn from these results is that both machines will result in the same travel distance, on the average, when just Part I of the algorithm is used to find the drilling sequence. When both Parts I and II are used to find the drilling sequence, there is a statistical difference between machines, and the IN-LINE machine will, on the average, result in the smaller travel distance. The percent increase that can be expected by using the QUAD instead of the IN-LINE machine amounts to 3.65%, however, this may be insignificant when compared to other engineering criteria used for selecting a machine to drill a PWB.

A comparison of the predicted travel distance given by the regression models developed for the QUAD and IN-Line machines (tables 11 vs. 13 for Part I and tables 12 vs. 14 for Part II) reveals that a contradiction exists with the conclusions drawn above. On the one hand, the predicted values for models 1 and 3 (Part I of the algorithm) indicate that a significant difference does exist between the two machines, and that the IN-LINE machine results in the longer travel distance. On the other hand, the predicted values for models 2 and 4 (Part II of the algoritm) indicate that there is not much difference between the machines and that the differences that do exist indicate the IN-LINE machine results in the longer travel distance. This contradiction can only be resolved by pointing out that the models developed for the IN-LINE machine do not fit the empirical results particularly well. As was previously stated, the reason for this is that there appears to be a causal relationship between spindle spacing and PWB length when the IN-LINE machine is used, which was not accounted for in the models. It is felt that further investigation of this relationship and the inclusion of this variable in the models, would improve the lack of fit and tend to support the conclusions drawn above.

CHAPTER VI.

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE STUDY

A. Conclusions

The general two part heuristic algorithm developed and evaluated in this paper provides a means of assigning spindles to holes if several spindles are capable of drilling the same hole size and for calculating good drilling sequences when non-turret, multiple spindle, numerically controlled, drilling machines are used to drill several holes sizes with one machine setup. While the technique given does not search for the true optimum solution for hole-spindle assignments and/or drilling sequences, the advantages of the technique include:

1. its simplicity in concept for solving a difficult pseudo-traveling salesman problem, where the first part of the algorithm is essentially a Nearest-Hole-Next sequencing solution that also uses this strategy for making spindle assignments when required. Once every hole has been assigned a unique spindle by Part I, the second part of the algorithm optimizes the drilling sequence using a standard traveling salesman problem algorithm developed by Shen Lin (7).

2. its capability of calculating (1) "optimum" or "near optimum" drilling sequences when each spindle used contains a different drill bit size, and (2) good drilling sequences when more spindles are available than there are number of hole sizes to be drilled and all of the available machine spindles are to be used (i.e., when several spindles contain the same size drill bit and an assignment of one of these spindles must be made to each hole

for the hole size involved).

3. its two part design which allows a part programmer the option of using just Part I for low production PWB drilling and/or the ability to further improve the drilling sequence by using Part II. In addition, the traveling salesman algorithm of Part II may be replaced by more efficient algorithms as they become available without major redesigns of the entire algorithm.

4. its capability of solving relatively large problems, up to 160-200 holes, in a reasonable amount of computation time relative to the production cost savings that can be realized. In addition, the size of the problem can easily be extended to 2000 holes or more if just Part I is used, without an unreasonable increase in computation time.

5. its applicability to turret type machines with only minor revisions of Part I to include the metrics developed in Chapter II. If verification of symmetry in the hole-to-hole time elements can be made, Part II can also be used to further improve the drilling sequence.*

The designed experiment approach for evaluating the algorithm yielded valuable information, from a user's standpoint, on what results can be expected from the algorithm for a wide variety of conditions. The regression equations developed for each part of the algorithm and for each machine evaluated, provides a means for estimating the expected value of total machine travel distance for a variety of applications.

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*Symmetry in the time or distance measurements between holes is not a requirement for Part I of the algorithm.

Although these equations are constrained by the conditions of the experiment, which only includes problems where multiple spindle holes are involved (i.e. several spindles available for drilling the same hole size), their development has provided a means for identifying and quantifying the significant variables that control the outcome of the algorithm. It is felt that the analysis performed in Chapter V provides a realistic evaluation of the performance that can be expected from the algorithm when the two types of non-turret machines examined in this paper are used in practice. The results of this analysis are summarized below.

1. Computation time for Part I was found to be proportional to the total number of holes squared and the number of multiple spindle holes squared, while the computation time for Part II (Shen Lin's algorithm) was found to be proportional to the total number of holes cubed and the number of 3-opt tours (or solutions) generated.* The magnitude of solution time for Part I was essentially negligible compared to that required for Part II (up to 30 minutes/3-opt tour generated for a 160 hole problem). Since the magnitudes of solution times for Part II are significantly large, careful consideration must be given to the economic trade-offs of computer costs versus expected production cost savings that can be achieved by using Part II. Additionally, generation of successive 3-opt tours in order to converge on "the optimum"

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*This latter statement is a foredrawn conclusion based on Shen Lin's own estimates in reference (7).

drilling sequence requires extremely large amounts of computation time with little or no gains from a practical standpoint, and therefore, the generation of one 3-opt tour appears to be sufficient for most applications.

2. The practice of drilling in the sequence of ascending X, Y coordinates and randomly assigning spindles to the multiple spindle holes (which might be done if no attempts were made to find better sequences) was found to be an extremely poor one. Savings in total travel distance of from 50 to 90 percent were noted when the solution of just Part I was compared to this method. If for no other reason, the use of at least Part I of the algorithm will greatly decrease the total machine cycle time required to drill a PWB.

3. No statistical difference in total efffective travel distance was found between the QUAD and IN-LINE machine when just Part I was used. Therefore, it does not matter which machine is chosen to drill a PWB if only Part I is to be used. When both Parts I and II were used, it was found that the IN-LINE machine, on the average, resulted in the lower travel distance, however, the difference amounted to only about 4%. Compared to other engineering criteria for selecting a machine, such as machine scheduling considerations, etc., this difference will probably be insignificant in practice.

4. It was found that the arrangement of drill bit sizes in the spindles for the QUAD machine had no statistical effect on travel distance and it is therefore concluded that it will not make any

difference how the drill bits are assigned to the spindles. On the other hand, a statistical difference was found between three different arrangements for the IN-LINE machine with the biggest difference noted when Part II was used. The amount of increase in travel distance by using the worst arrangement was found to be approximately 6%.

5. The drilling area of a PWB and the total number of holes to be sequenced was found to have a significant influence on the total travel distance resulting from both parts of the algorithm. In general, as the area and/or the total number of holes increased, the travel distance also increased. Additionally, it was found that the expected decrease in travel distance that resulted by using Part II became larger as these two factors increased. The conclusion is that, for the same number of total holes, Part II of the algorithm becomes more efficient as the area of the PWB increases since a larger savings in travel distance is gained for the same amount of computation time. In contrast, it was found that as the number of multiple spindle holes increased, the total travel distance for each part of the algorithm, as well as the difference between the travel distances resulting from Part I and Part II, decreased. It is concluded from these results, that if fewer hole sizes are to be drilled than there are spindles available, a smaller travel distance can be expected by using all the spindles and allowing the algorithm to assign the spindles to the multiple spindle holes. In addition, if a decision must be made on which hole size to assign the duplicate spindles to,

the hole size with the most number of holes should be chosen.

B. Recommendations for future study

Further investigation into solutions for the sequencing problem presented by multiple spindle machines should include an empirical evaluation of typical types of turret drilling machines. Also, more data may be desirable for intermediate levels of area in order to sharpen the predictive power of the regression equations developed.

Even though the effects of drill bit placement in the spindles was found to be minor, there still may be justification for reiterating Part I of the algorithm, for all the arrangements possible, and then selecting the arrangement that results in the smallest travel distance for a given problem. It was noted, however, that when Part II was used, the best arrangement for Part I was not always the best for Part II, therefore, this suggestion may only be reasonable when just Part I is used. A bolder approach to this problem would be to develop an algorithm that determines how many drill bits of the same size should be used and what placement in the spindles would be the best. In addition, the possibilities of simultaneous drilling can be further investigated. This condition is somewhat limited to the use of certain types of drilling machines, but if simultaneous drilling is possible in a given problem, a real reduction in total drilling time and problem size can be realized.

Further study in the area of true optimum seeking algorithms is needed to evaluate the quality of solution provided by each part of the algorithm. If optimum seeking algorithms can be developed, using perhaps the Branch-and-Bound methology, the results presented in this paper can be used to compare the efficiency of the proposed solution procedures.

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APPENDIX A

DETAILED FLOW CHARTS OF SOLUTION PROCEDURE AND PROBLEM GENERATOR

Notation for the detailed flow charts is given below. In general, lower case letters indicate subscripts and indices.

Variable Name and Definition

n = total number of holes to be sequenced.

ns = number of hole sizes to be drilled.

np = number of available spindles/work station on the machine

= 4

X(i),Y(i) = X,Y coordinates of hole i, i = 1, ..., n.

H(i) = hole size of hole i , i = 1, ..., n.

SX(k),SY(k) = X,Y coordinates of spindle k relative to machine origin, k = 1, ..., np.

SPA(k) = hole size assigned to spindle k, k = 1, ..., np.

SP(i,j) = work matrix for hole size i, i = 1, ..., ns

where SP(i,1) = number of spindles assigned to hole size i.

SP(i,j) = spindle number(s) assigned to drill hole size i, j = 2, ..., np + 1.

DBM = effective travel distance of bench mark rule.

RN,RN1,RN2 = random numbers between 0 and 1.

V(i) = work vector for Part I, i = 1, ..., n-1

T(i) = hole drilling sequence for Part I and II, i = 1, ..., n.

DIST = effective travel distance for the drilling sequence developed by Part I.

D(i,j) = effective travel distance matrix for Part II,

i,j = 1, ..., n.

DX,DY = X,Y dimensions of the printed wiring board.

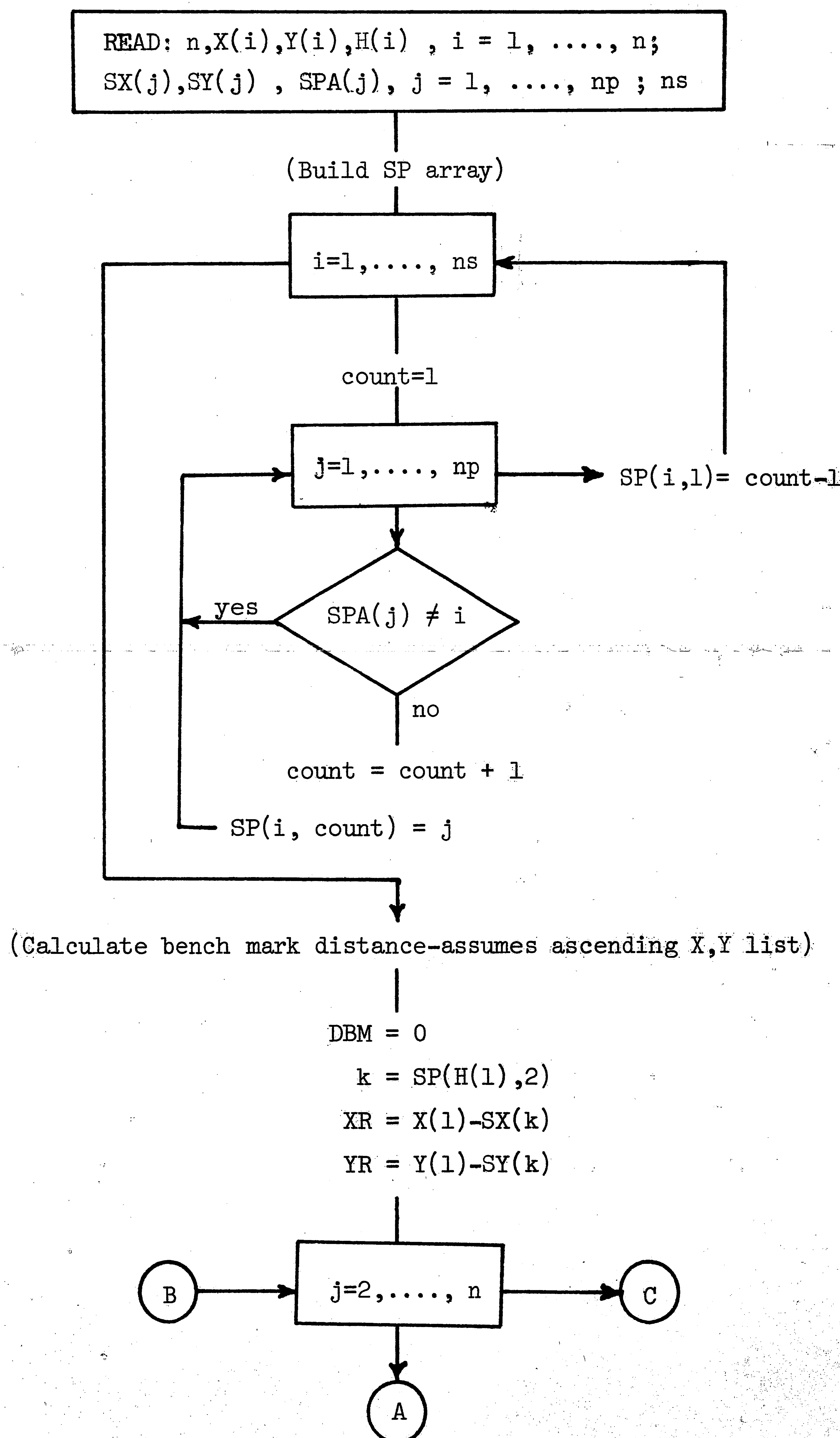
NH(j) = number of holes/hole size j, j = 1, ..., ns.

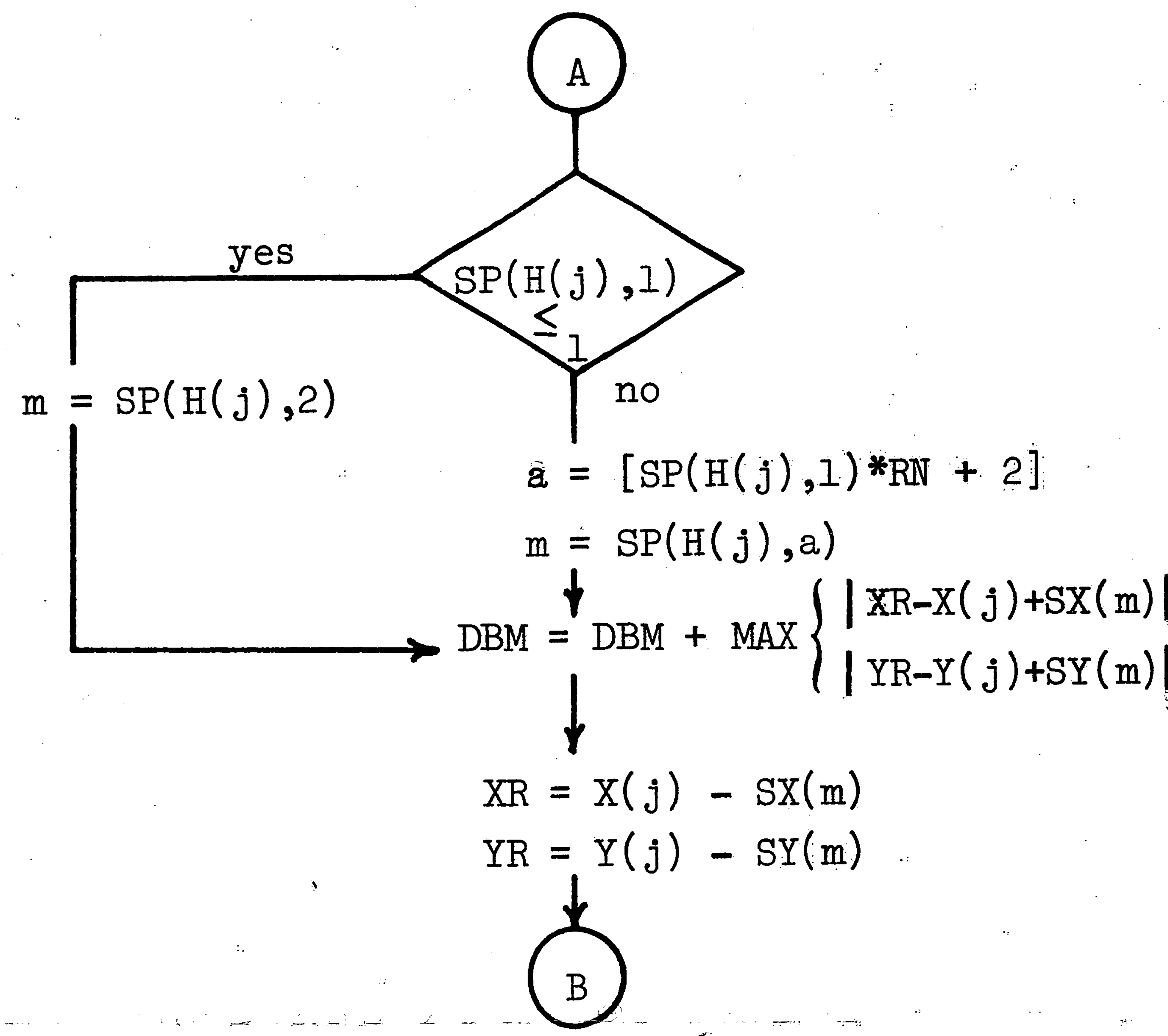
P(j) = fraction of n/hole size j, j = 1, ..., ns.

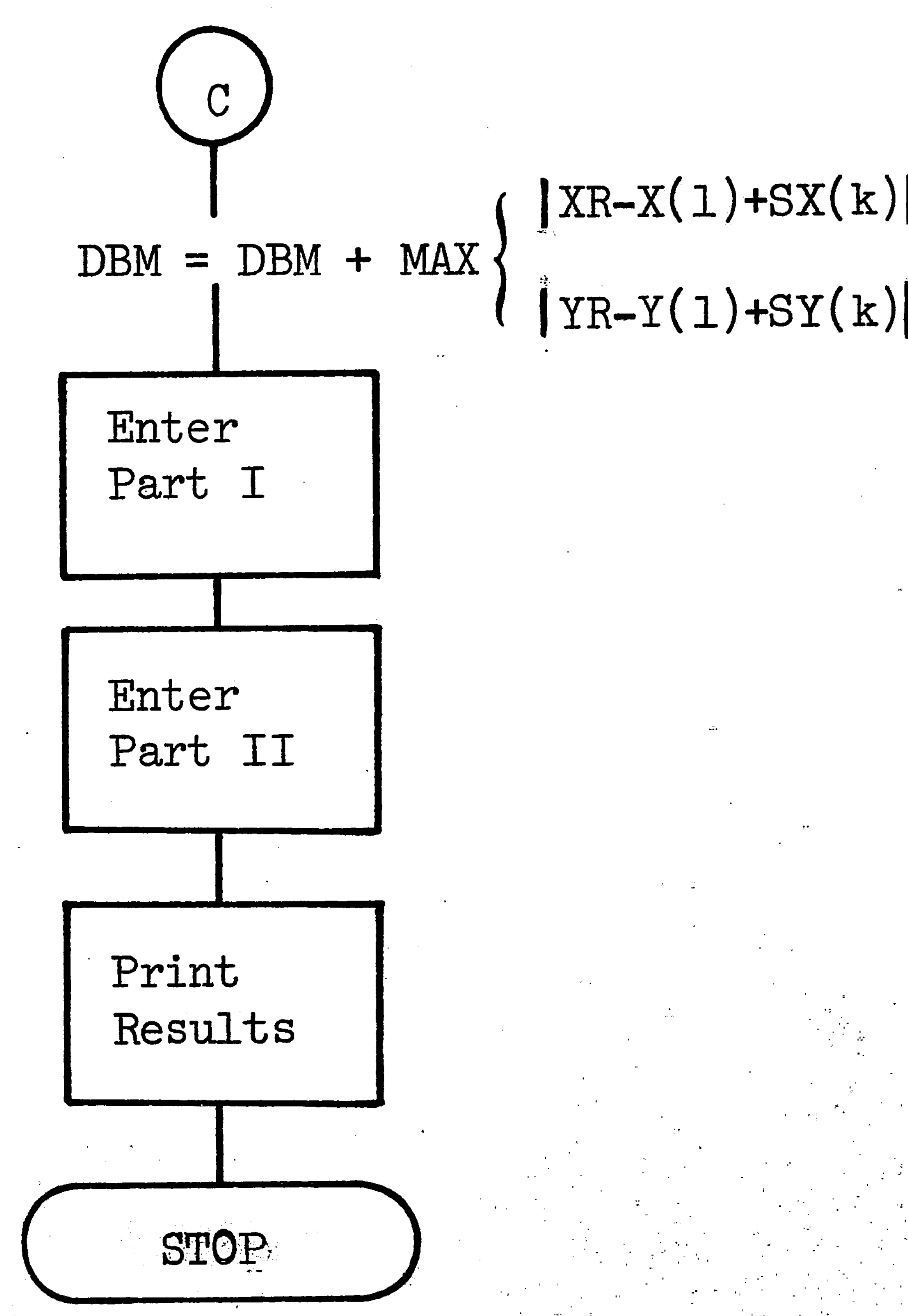
KEY(i) = array used for sorting the X,Y coordinate list,

i = 1, ..., n.

MAINLINE


READ: n,X(i),Y(i),H(i) , i = 1, ..., n;
SX(j),SY(j) , SPA(j), j = 1, ..., np ; ns
(Build SP array)
i=1,...., ns
count=1
j=1,...., np
SP(i,1)= count-1
SPA(j) ≠ i
yes
no
count = count + 1
SP(i, count) = j
(Calculate bench mark distance-assumes ascending X,Y list)
DBM = 0
k = SP(H(1),2)
XR = X(1)-SX(k)
YR = Y(1)-SY(k)
B
j=2,...., n
C
A


A
yes
SP(H(j),1) ≤ 1
no
m = SP(H(j),2)
a = [SP(H(j),1)*RN + 2]
m = SP(H(j),a)
DBM = DBM + MAX { |XR-X(j)+SX(m)|, |YR-Y(j)+SY(m)| }
XR = X(j) - SX(m)
YR = Y(j) - SY(m)
B


C
DBM = DBM + MAX { |XR-X(1)+SX(k)|, |YR-Y(1)+SY(k)| }
Enter Part I
Enter Part II
Print Results
STOP

PART I - NEAREST HOLE NEXT

nn=n-1

V(i)=i+1, i=1,....,n-1

DIST=0

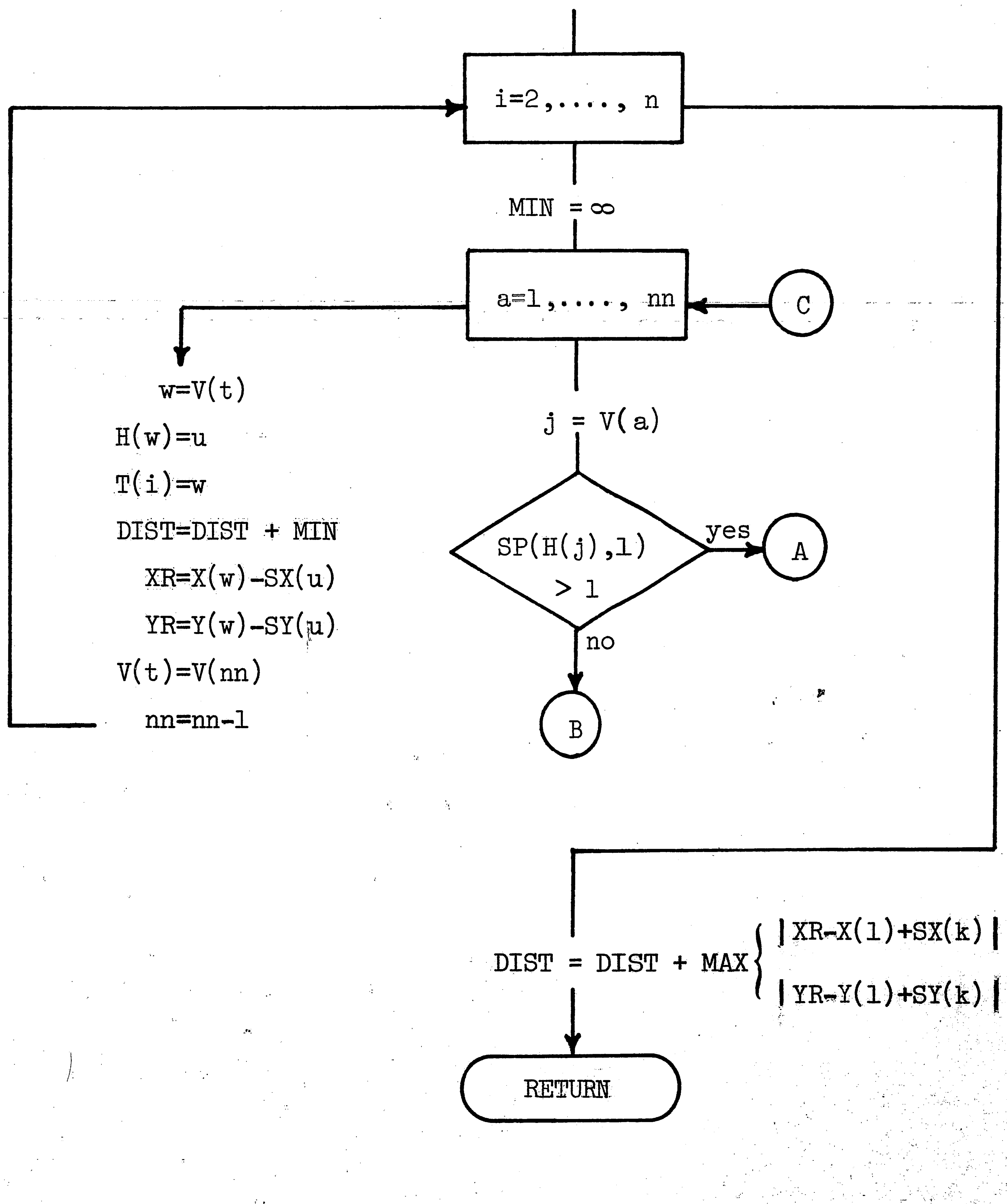
k=SP(H(1),2)

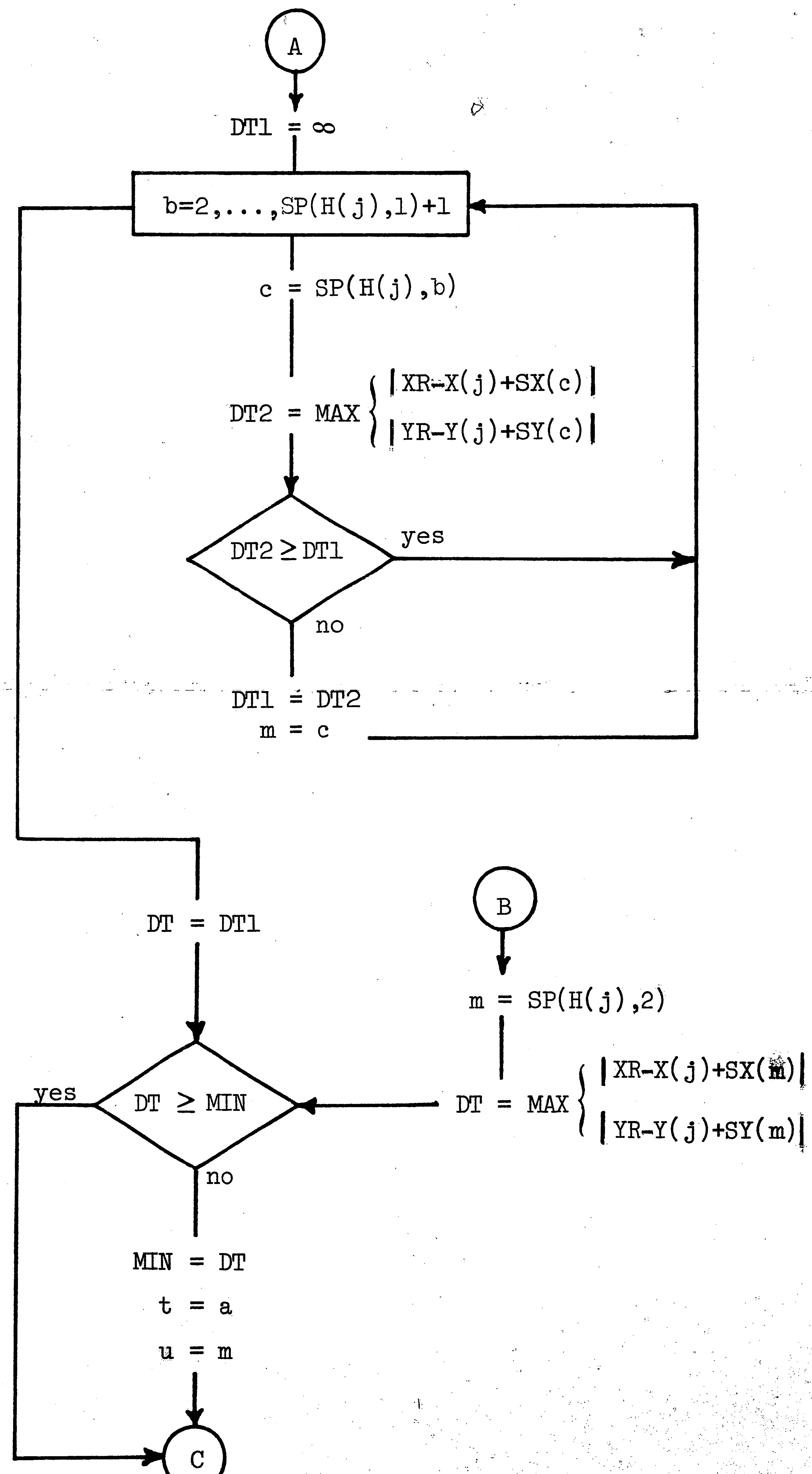
H(1)=k

T(1)=1

XR=X(1)-SX(k)

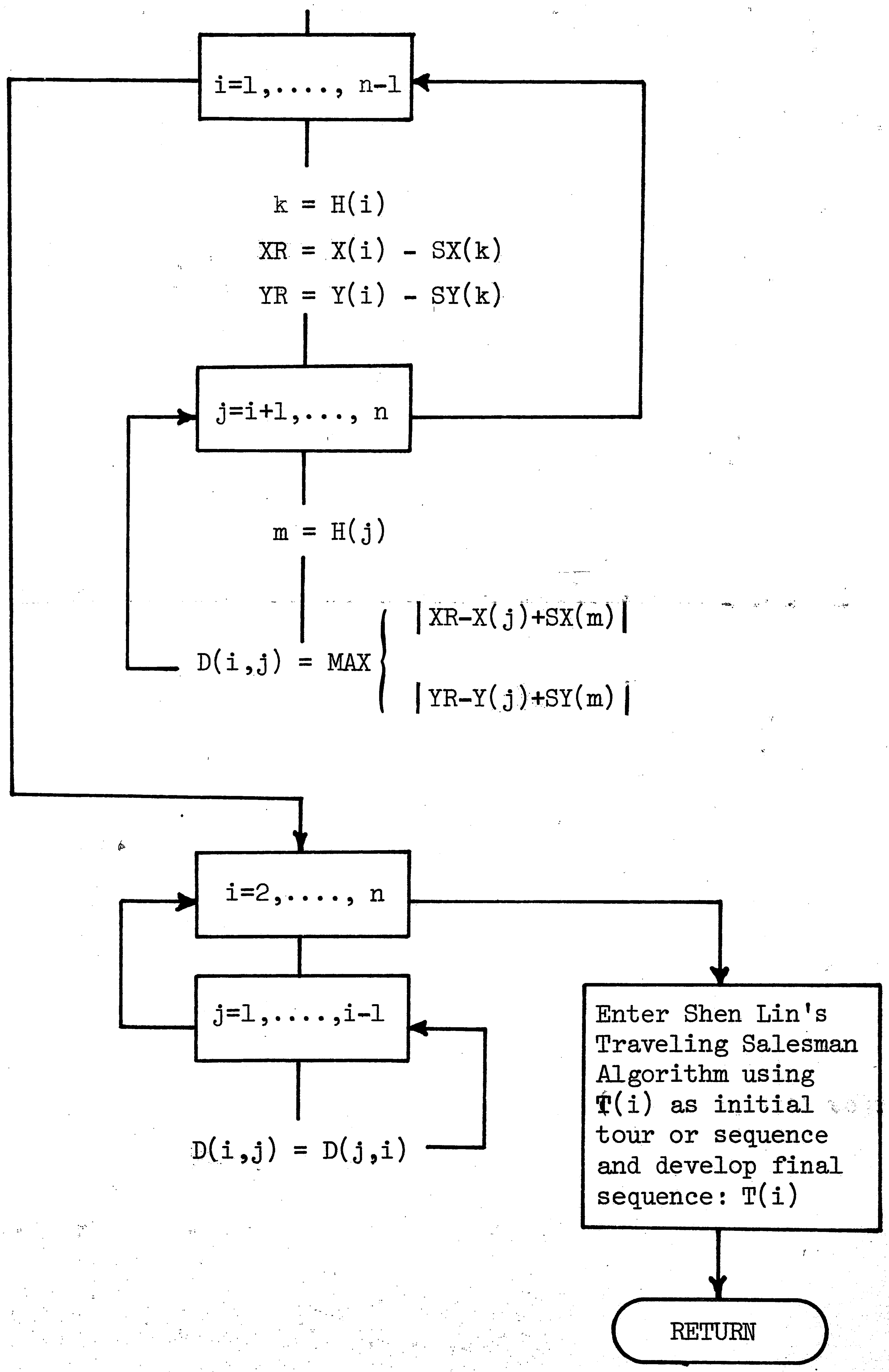
YR=Y(1)-SY(k)



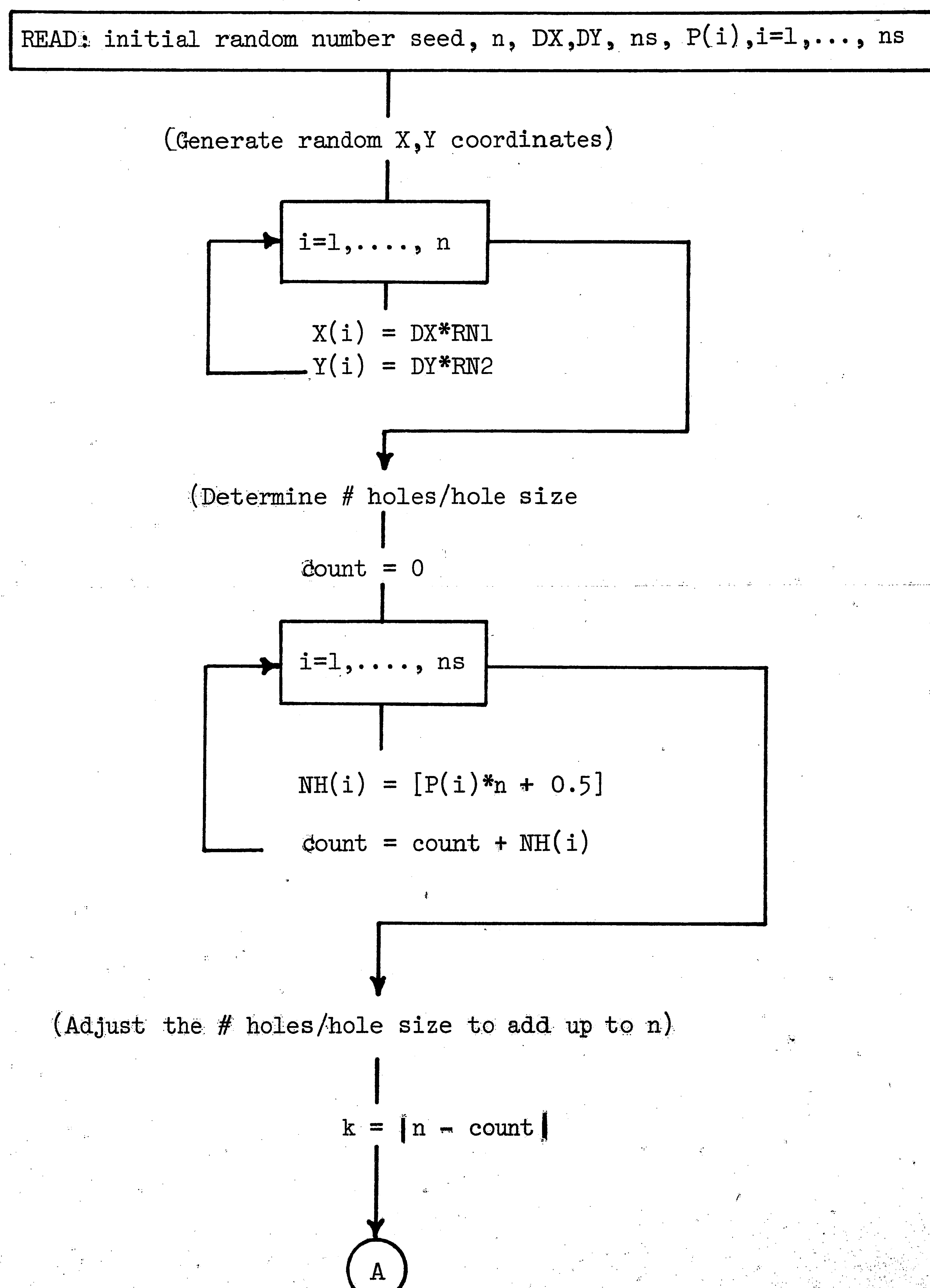

A
DT1 = ∞
b=2,...,SP(H(j),1)+1
c = SP(H(j),b)
DT2 = MAX |XR-X(j)+SX(c)| |YR-Y(j)+SY(c)|
DT2 ≥ DT1
yes
no
DT1 = DT2
m = c
DT = DT1
B
m = SP(H(j),2)
DT = MAX |XR-X(j)+SX(m)| |YR-Y(j)+SY(m)|
DT ≥ MIN
yes
no
MIN = DT
t = a
u = m
C

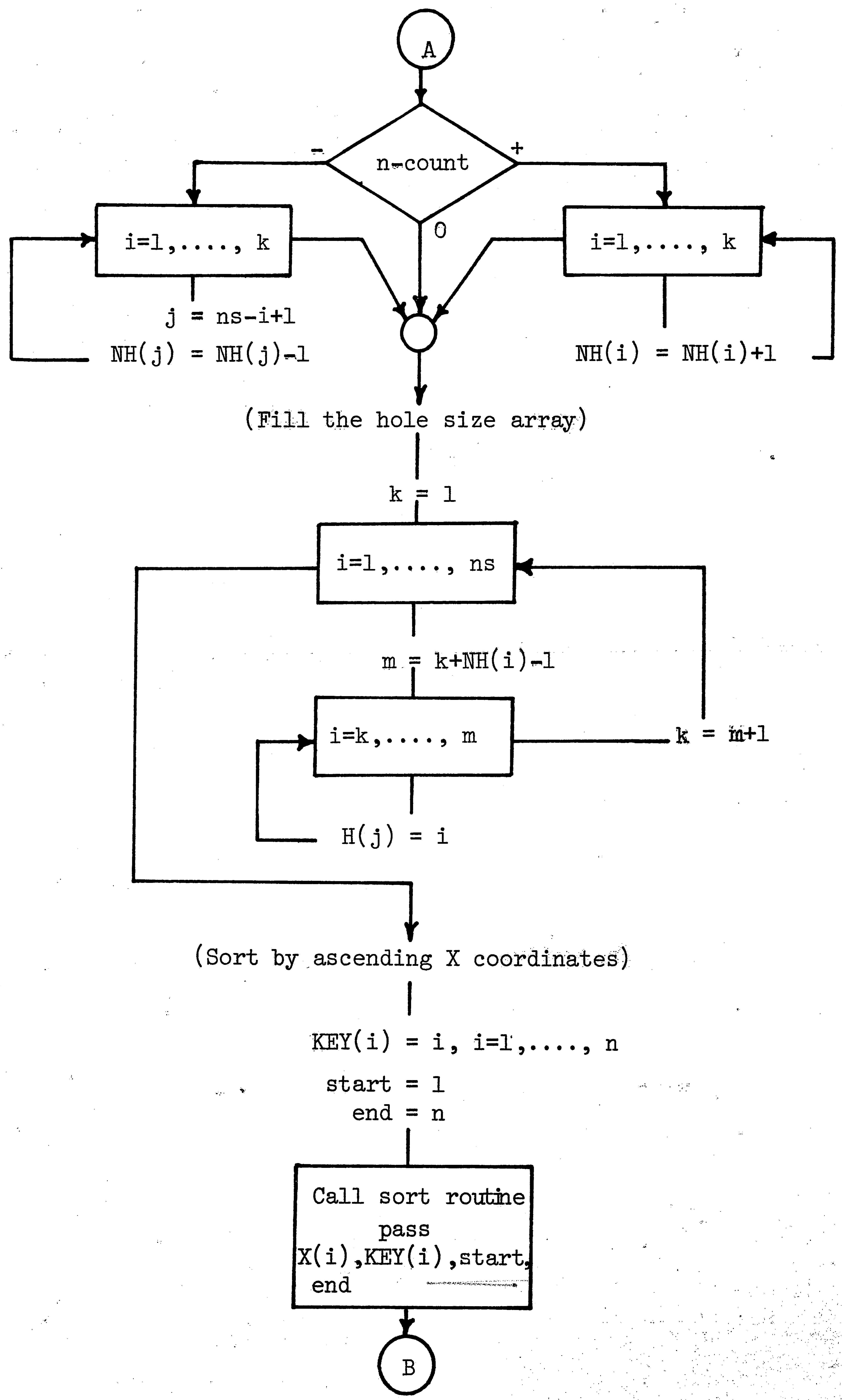
PART II - TRAVELING SALESMAN SOLUTION

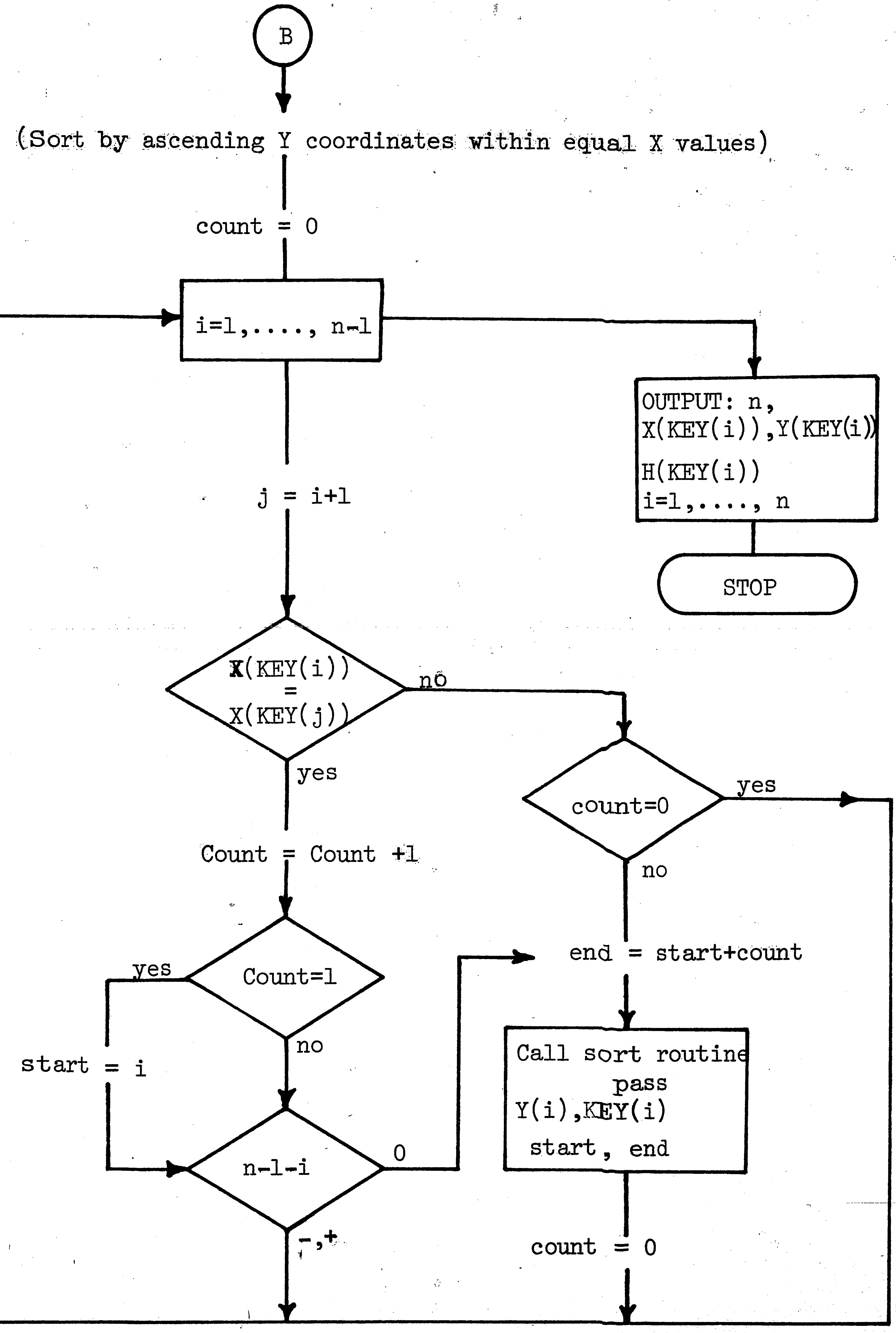
(Calculate Effective Distance Matrix)



PROBLEM GENERATOR

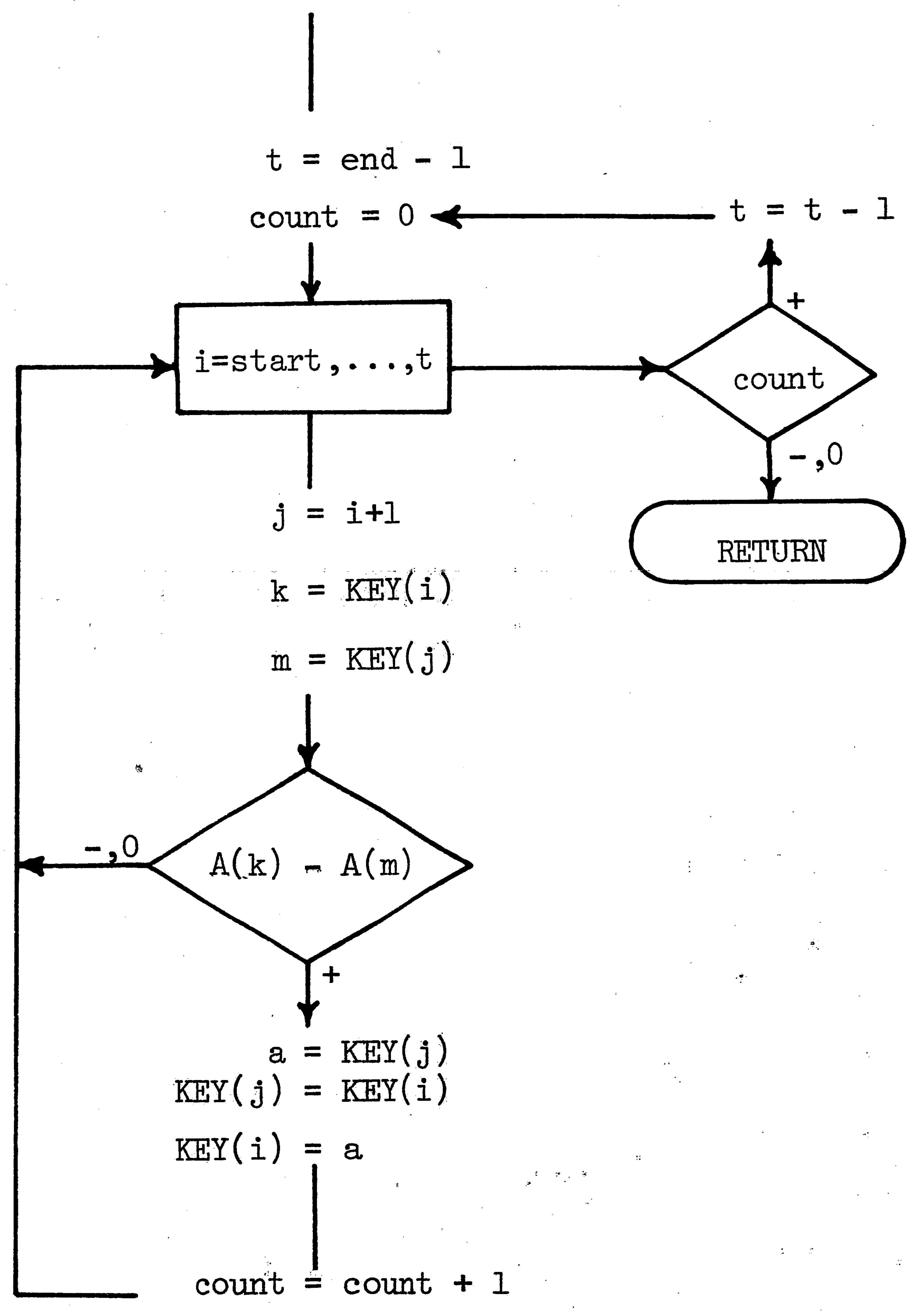



A
n-count
-
+
0
i=1,...., k
j = ns-i+1
NH(j) = NH(j)-1
i=1,...., k
NH(i) = NH(i)+1
(Fill the hole size array)
k = 1
i=1,...., ns
m = k+NH(i)-1
i=k,...., m
k = m+1
H(j) = i
(Sort by ascending X coordinates)
KEY(i) = i, i=1,...., n
start = 1
end = n
Call sort routine
pass
X(i),KEY(i),start,
end
B


B
(Sort by ascending Y coordinates within equal X values)
count = 0
i=1,...., n-1
OUTPUT: n,
X(KEY(i)),Y(KEY(i))
H(KEY(i))
i=1,...., n
STOP
j = i+1
X(KEY(i))
=
X(KEY(j))
no
yes
count=0
yes
no
Count = Count +1
Count=1
yes
no
end = start+count
start = i
Call sort routine
pass
Y(i),KEY(i)
start, end
n-1-i
0
-,+
count = 0

SORTING SUBROUTINE

(Bubble sort on low value first. Values passed = start,end,KEY(i) X(i) or Y(i) and A(i) = X(i) or Y(i), i = 1, ..., n)



APPENDIX B

EXPERIMENTAL RESULTS

Notation

$A1 = 24 \text{ in}^2$

$A2 = 280 \text{ in}^2$

N1 = 40 holes

N2 = 100 holes

N3 = 160 holes

F1 = .34

F2 = .90

F3 = 1.00

P1, P2, P3 = see page 44 for definition

QUAD MACHINE RESULTS
TOTAL EFFECTIVE TRAVEL DISTANCE IN INCHES
RESULTING FROM: BENCH MARK RULE

		3 Hole Sizes				2 Hole Sizes	
		F1		F2		F3	
		P1	P2	P1	P2	P1	P2
A1	N1	1 88.857	1 79.622	2 101.579	2 78.518	3 81.992	3 78.421
	N2	4 187.165	4 210.144	5 214.403	5 199.919	6 203.392	6 215.289
	N3	13 370.574			14 292.723		15 351.967
A2	N1	7 211.398	7 209.059	8 203.857	8 212.967	9 209.330	9 188.051
	N2	10 552.198	10 550.804	11 480.023	11 461.338	12 495.975	12 497.159
	N3		16 785.696	17 756.563		18 750.387	

QUAD MACHINE RESULTS
TOTAL EFFECTIVE TRAVEL DISTANCE IN INCHES
RESULTING FROM: PART I

		3 Hole Sizes				2 Hole Sizes	
		F1		F2		F3	
		P1	P2	P1	P2	P1	P2
A1	N1	1 32.808	1 34.634	2 23.942	2 34.483	3 21.996	3 20.933
	N2	4 50.731	4 54.083	5 37.081	5 38.896	6 40.092	6 44.319
	N3	13 73.903			14 51.478		15 58.587
A2	N1	7 95.846	7 90.027	8 82.295	8 95.523	9 88.894	9 83.095
	N2	10 151.185	10 157.211	11 131.181	11 125.273	12 126.478	12 135.076
	N3		16 194.368	17 178.665		18 152.103	

QUAD MACHINE RESULTS
TOTAL EFFECTIVE TRAVEL DISTANCE IN INCHES
RESULTING FROM: PART II (1ST 3-OPT TOUR)

		3 Hole Sizes				2 Hole Sizes	
		F1		F2		F3	
		P1	P2	P1	P2	P1	P2
A1	N1	1 28.226	1 29.969	2 21.878	2 26.276	3 20.116	3 19.537
	N2	4 43.720	4 43.988	5 32.349	5 33.235	6 30.983	6 37.193
	N3	13 56.327			14 46.068		15 46.802
A2	N1	7 71.813	7 76.800	8 70.843	8 73.411	9 76.567	9 72.018
	N2	10 126.914	10 122.307	11 112.016	11 110.504	12 113.686	12 111.657
	N3		16 152.785	17 138.211		18 127.339	

IN-LINE MACHINE RESULTS
TOTAL EFFECTIVE TRAVEL DISTANCE IN INCHES
RESULTING FROM: BENCH MARK RULE

		3 Hole Sizes						2 Hole Sizes		
		F1			F2			F3		
		P1	P2	P3	P1	P2	P3	P1	P2	P3
A1	N1	1 124.907	1 108.952	1 111.081	2 108.455	2 144.613	2 87.823	3 111.332	3 117.238	3 123.142
	N2	4 274.802	4 251.147	4 277.943	5 290.087	5 387.281	5 210.383	6 312.177	6 287.544	6 307.031
	N3	13 471.214	13 408.640	13 459.942	14 418.608	14 546.350	14 332.274	15 464.916	15 437.755	15 499.414
A2	N1	7 210.469	7 222.072	7 209.238	8 223.366	8 243.753	8 210.967	9 215.572	9 216.853	9 221.204
	N2	10 579.398	10 560.160	10 571.656	11 506.939	11 567.398	11 479.254	12 531.292	12 533.305	12 536.371
	N3	16 875.245				17 869.896		18 808.242		

IN-LINE MACHINE RESULTS
TOTAL EFFECTIVE TRAVEL DISTANCE IN INCHES
RESULTING FROM: PART I

		3 Hole Sizes						2 Hole Sizes		
		F1			F2			F3		
		P1	P2	P3	P1	P2	P3	P1	P2	P3
A1	N1	1 38.842	1 32.533	1 33.227	2 34.199	2 31.851	2 37.235	3 21.697	3 24.319	3 27.631
	N2	4 56.818	4 53.287	4 49.107	5 49.073	5 50.147	5 40.533	6 47.410	6 45.331	6 48.556
	N3	13 67.268	13 62.385	13 65.649	14 55.076	14 58.940	14 58.077	15 44.010	15 58.431	15 49.905
A2	N1	7 89.305	7 98.905	7 84.847	8 76.556	8 90.580	8 97.667	9 79.623	9 90.448	9 92.448
	N2	10 165.825	10 155.133	10 153.522	11 146.493	11 131.728	11 137.793	12 134.701	12 137.313	12 171.254
	N3	16 196.696				17 178.130		18 137.558		

IN-LINE MACHINE RESULTS
TOTAL EFFECTIVE TRAVEL DISTANCE IN INCHES
RESULTING FROM: PART II (1ST 3-OPT TOUR)

		3 Hole Sizes						2 Hole Sizes		
		F1			F2			F3		
		P1	P2	P3	P1	P2	P3	P1	P2	P3
A1	N1	1 28.011	1 28.125	1 28.544	2 24.372	2 27.958	2 31.362	3 17.809	3 22.232	3 26.177
	N2	4 46.157	4 43.982	4 43.309	5 39.940	5 40.076	5 35.473	6 41.404	6 38.134	6 33.943
	N3	13 54.819	13 54.082	13 53.060	14 43.973	14 50.234	14 48.016	15 40.698	15 50.103	15 45.455
A2	N1	7 73.344	7 73.340	7 76.323	8 69.274	8 75.509	8 69.618	9 76.896	9 77.147	9 88.902
	N2	10 126.917	10 122.811	10 132.047	11 117.122	11 114.990	11 126.653	12 109.710	12 118.510	12 123.784
	N3	16 158.693				17 127.549		18 118.972		

VITA

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Wife:	Lois E.
Children:	Scott E.

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Western Electric Co., Inc.
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